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PAL DECODING:

Multi-dimensional filter design for chrominance-luminance separation

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Research Department, Engineering Division
THE BRITISH BROADCASTING CORPORATION

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PAL DECODING: MULTI-DIMENSIONAL FILTER DESIGN FOR CHROMINANCE-LUMINANCE SEPARATION

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Summary

The introduction of digital studio equipment using YUV component signals has led to a requirement for PAL decoders with improved chrominance-luminance separation performance. The form of the PAL signal in terms of its three-dimensional spectrum is described as an aid to the design of multi-dimensional comb filters. The performance of non-adaptive line-delay based comb filters is reviewed in this context and the extension of these basic methods to use field and picture delays is considered. As none of these methods is entirely satisfactory, an improved method has been developed by combining line and field delays into a four-field multi-tap decoder.

The possibility of further improvements is investigated by developing a design technique which allows the filter characteristic to be specified freely within the fundamental limitations of the filter size. The method is used to design a decoder with filter apertures of eight fields by four lines, the performance of which is then compared with that of other less complex circuits. The results of subjective tests show that, although better in some circumstances, the eight-field decoder causes increased impairments to moving chrominance. The significantly simpler four-field decoder, however, maintains reasonably good performance throughout and represents a substantial improvement over conventional decoding techniques.

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1. INTRODUCTION

The PAL colour television system[1] carries the colour difference signals as a pair of quadrature modulated subcarriers in the high frequency part of the luminance spectrum. This allows the extra colour information to be transmitted within the bandwidth limits allocated for monochrome signals. It also provides a degree of compatibility with monochrome receivers because the high frequency subcarrier patterns are only noticeable in highly coloured areas of the scene and are not very obtrusive at normal viewing distances.

Because the luminance and modulated subcarrier components share the same region of the video spectrum, it is often impossible to separate them perfectly in a decoder. This leads to the impairments known as cross-colour (luminance decoded as chrominance) and cross-luminance (unsuppressed subcarrier). A conventional PAL decoder, such as that found in most domestic television sets, can produce substantial amounts of these impairments, although the quality of the viewed picture is usually adequate.

However, decoders are also used in studios to allow encoded colour signals to be processed in the form of separate luminance and chrominance components. This is particularly important in the context of a changeover to digital *YUV* component studios, where contributions from PAL-encoded sources need to be decoded to enter the *YUV* areas. In these applications, the signals are subsequently to be recoded to PAL for broadcast transmission.

PAL signals can be decoded in such a way that the resulting *YUV* signals can be recoded to reproduce the original signals exactly. Perfect reversibility depends on two factors: first, the luminance and chrominance filtering characteristics used in the decoder have to be complementary, and secondly, the chrominance components have to be recoded with the same subcarrier phase and PAL switch sense as was used in the original coding process. This ensures that any residual cross-effects, left in the component signals by the decoder, recombine to form the original PAL signal. However, signal processing such as two-field editing, still frames or special effects would alter these cross-components, thus destroying the reversible properties of the signal. This makes the reversible technique unsuitable for most studio applications.

Instead, a decoder for digital studios has to achieve a high degree of separation because any residual cross-effects left by the studio decoder could then interfere with the true signals produced by the second coder, ultimately producing more serious impairments at the domestic decoder[2]. For these applications, the advantages of digital processing also apply to the studio decoder itself, particularly to gain the performance stability and filter accuracy of digital circuitry.

The main processes of a colour decoder consist of separating the luminance and chrominance, and demodulating the chrominance to produce two colour difference signals. A previous Report[3] has described the demodulation process in some detail. Also, other Reports have considered some of the possibilities for chrominance—luminance separation. The current work grew from an investigation of decoding methods for use in digital standards conversion[4]. This compared the chrominance—luminance separation performance of several comb filters based on line delays and a number of reasonably effective methods were developed. However, it was found that the vertical—temporal interpolator of the standards converter, used to synthesise new signals for the lines and fields of the output standard, proved even more effective than the decoder for suppressing cross-effects[5].

A number of vertical and temporal comb filters had been suggested previously for PAL decoding[6], but the complication of such techniques made them impracticable until reasonably cheap digital storage devices became available[7]. Some of these possibilities were briefly examined for studio decoding applications, along with methods devised more recently[2]. These showed spectacular performance for still pictures, although this was marred by serious impairments to moving areas of picture. Some movement adaptive techniques were briefly investigated to overcome the impairments[2], but the approach was discontinued because of escalating complication. Considerable effort is nevertheless being devoted to the development of motion detection for other applications, and its eventual use in PAL decoding should not be discounted. For the time being, however, further development was directed towards improved comb filters, in particular, attempting to synthesise the required vertical—temporal frequency characteristics, rather than choosing a moderately acceptable response from those obtained from known comb filters.

This Report first describes the different components present in the vertical—temporal spectrum of PAL signals, both before and after demodulation. Then the performance characteristics of the original line-based comb filters are examined, followed by the extension of the line-based techniques to use field and picture delays. While the simple comb filters often produce good performance in some respects, this is accompanied by poor performance in others. So, developments of the simple filters into multi-tap combs are described. It is difficult, however, to extend the development very far in this way, so a method of synthesising a desired response is included. The optimised decoder filters devised using this method are then compared against those developed previously.

2. THE PAL SPECTRUM IN THREE DIMENSIONS

Some of the deficiencies of conventional domestic decoders can be overcome by using comb filtering techniques to provide additional degrees of freedom for the optimisation of filter responses. Although comb filter action can be explained by detailed examination of the comb 'teeth' in the conventional one-dimensional horizontal frequency spectrum, a much better understanding can be obtained by using the vertical and temporal frequency dimensions as well[6]. In these dimensions, the sampling action of the television raster scan has a considerable effect as described in the following section.

2.1 Effects of scanning

The brightness of an image falling on to a television camera tube is a function varying in three dimensions: horizontal position (x), vertical position (y) and time (t). The action of scanning the image converts this three-dimensional function into a one-dimensional signal. In the scanned signals the horizontal dimension is still continuous, but the image brightness is now only defined at discrete intervals in the vertical and temporal dimensions. Thus the image brightness has been sampled in the two dimensions of vertical position and time.

The action of sampling repeats the frequency spectrum of the image at harmonics of the sampling frequency. The image spectrum consists of horizontal frequency (m), vertical frequency (n) and temporal frequency (f) components. Horizontal frequencies in the image are not affected by scanning because the horizontal dimension of the signal remains continuous. Therefore, only the vertical and temporal components of the image spectrum, represented diagrammatically in Fig. 1, are affected by scanning.

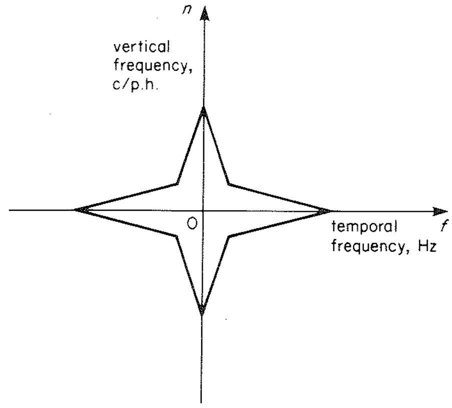


Fig. 1 - A representation of the main features of the vertical—temporal frequency spectrum of an image.

If the scene from which the image is formed is completely still, then the frequencies which make up the image spectrum have no temporal component and all the spectral energy lies along the vertical frequency axis. If an object in the scene appears and disappears at a regular rate, such as a light flashing, this results in temporal frequency components that are positioned away from the n axis by an amount depending on the rate of flashing. However, most temporal frequencies are produced by the movement of objects within the scene. The effect of movement is more complicated because the temporal frequencies produced depend on both the rate of movement and the spatial frequencies that make up the object. For purely horizontal movement, all the spectral energy is concentrated along the f axis of the n—f spectrum. If, instead, an object is moving vertically, this produces a series of temporal components along a diagonal line passing through the origin; the angle made between this line and the n axis increases with the speed of movement of the object.

There is virtually no limit to the spatial and temporal frequencies that can occur in a scene, but some filtering is introduced by the action of the camera. The camera tube integrates the light falling on it at each point for a field period, thus attenuating the higher temporal frequencies. (It is generally assumed that interlaced line positions are discharged on each field scan). Also, the scanning spot is of finite width, so that the charge from adjacent areas of the tube surface contributes to the output current, thereby filtering the image vertically.

Thus the scanned spectrum consists of the spectrum of the image, Fig. 1, filtered by the camera characteristic and repeated at harmonics of the scanning rates. An interlaced scanning standard with 625 lines per picture and 50 fields per second produces the spectrum shown in Fig. 2. Although only the first quadrant is shown, the spectrum extends into the other quadrants with the same pattern.

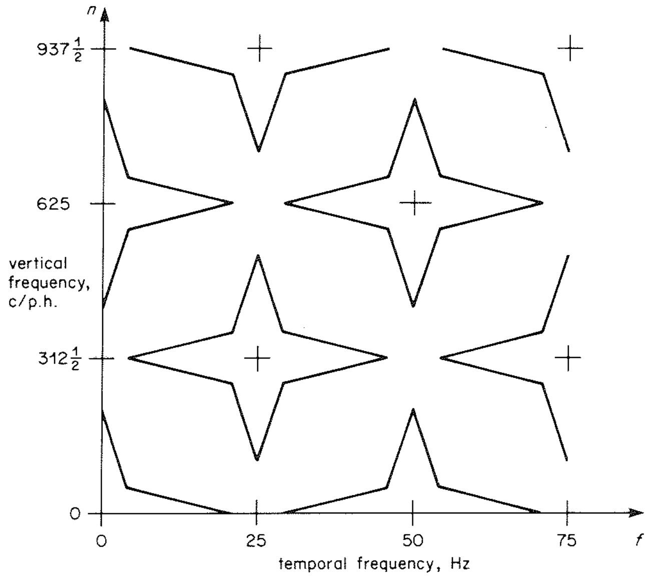


Fig. 2 - The effect of television scanning in the frequency domain: the 625 lines per picture, 50 fields per second interlaced scan repeats the spectrum of the image (Fig. 1) at harmonics of the scanning rates.

As components of the spectra can extend well beyond the outlines shown in Fig. 2, aliasing forms an accepted part of normal television pictures. For example, with interlaced scanning, flicker arises from vertical frequency components in the region around (0, 312½) in the image spectrum. In the scanned spectrum these components are repeated around (25, 0), arising from the spectra centred on (25, ± 312½). So the vertical detail flashes with a temporal frequency of 25 Hz.

2.2 Modulated subcarrier signals

The colour subcarrier frequency used in the PAL system was chosen to minimise the visibility of the subcarrier dot pattern produced on monochrome receivers. Because of this, besides being a high horizontal frequency, the subcarrier has a high vertical frequency component to ensure that there is a phase change from line to line and a high temporal frequency component to produce a phase change from picture to picture. Thus, the centres of the modulated chrominance components in the vertical–temporal spectrum are well separated from the main luminance frequencies as shown in Fig. 3. The offset between the U and V components results from the inversion of the V signal on alternate lines, known as the PAL switch.

The colour difference signals produced from the image contain vertical and temporal components similar to those described in Section 2.1. In the PAL encoded signal, these appear as sidebands extending from the colour subcarrier frequencies, Fig. 3. For vertical frequencies, the sidebands extend from the subcarrier positions along lines parallel to the n axis, while for temporal frequencies, as might be produced by a coloured object moving horizontally, the sidebands extend parallel to the f axis. However, the colour difference signals usually have a horizontal bandwidth of about 1 MHz, much lower than that of the luminance signals. Because of this, horizontal movement produces much less high temporal frequency energy in the colour difference signals. For this reason the extent of the temporal chrominance sidebands shown in the diagram is less than that shown for luminance.

The positions of the U and V subcarriers are interchanged for positive and negative values of m. Thus, the U subcarrier is located at (18¾, 78⅛), (−6¼, −234⅜), etc. for positive values of m, and at (6¼, 234⅜), (−18¾, −78⅛), etc. for negative values of m.

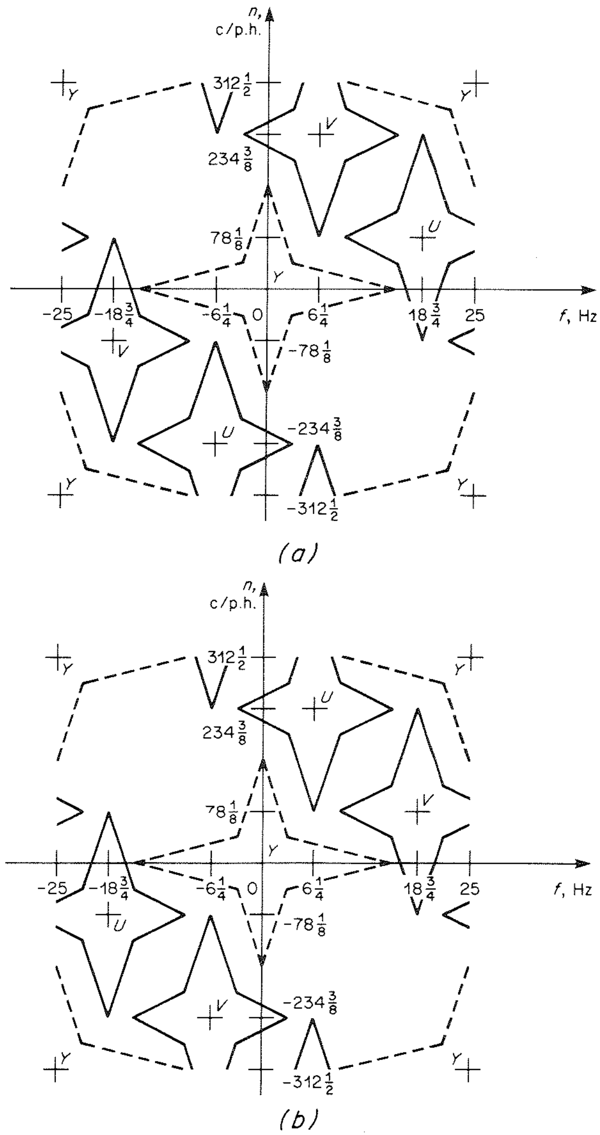


Fig. 3 - Positions of the main chrominance and luminance components in the vertical–temporal spectrum of 625/50 PAL-encoded colour television signals:

(a) for positive values of horizontal frequency
(b) for negative values of horizontal frequency

Luminance (Y) regions are marked with a dashed outline.

As well as being orthogonally phased, the V subcarrier has offsets of −12½ Hz and 156¼ c/p.h. from the U subcarrier position due to the modulating action of the V-axis switch. These positions, shown in Fig. 3, minimise the visibility of the subcarriers by giving the highest combinations of temporal and vertical frequency consistent with the offset resulting from the V-axis switch.

2.3 Chrominance demodulation

Chrominance demodulation consists of multiplying the modulated chrominance signals by subcarrier frequency sine and cosine waves. Accordingly, in the frequency domain, the modulated chrominance spectrum is convolved with an impulse function at each subcarrier position. In the n–f plane, this shifts the U components to be centred on the origin, as shown in Fig. 4(a). Any luminance components entering the demodulators to produce cross-colour are similarly shifted in frequency to be centred on the positions previously occupied by the subcarriers. Thus, the cross-colour components Y'_{+m} are centred on (6¼, 234⅜) and (18¾, 78⅛). The spectrum for demodulated V signals, shown in Fig. 4(b), is similar, with both the U and V positions and the cross-colour $+m$ and $-m$ positions interchanged. The demodulation process also shifts chrominance information to twice the subcarrier frequency, but these components are removed by the horizontal low-pass filters of the demodulators.

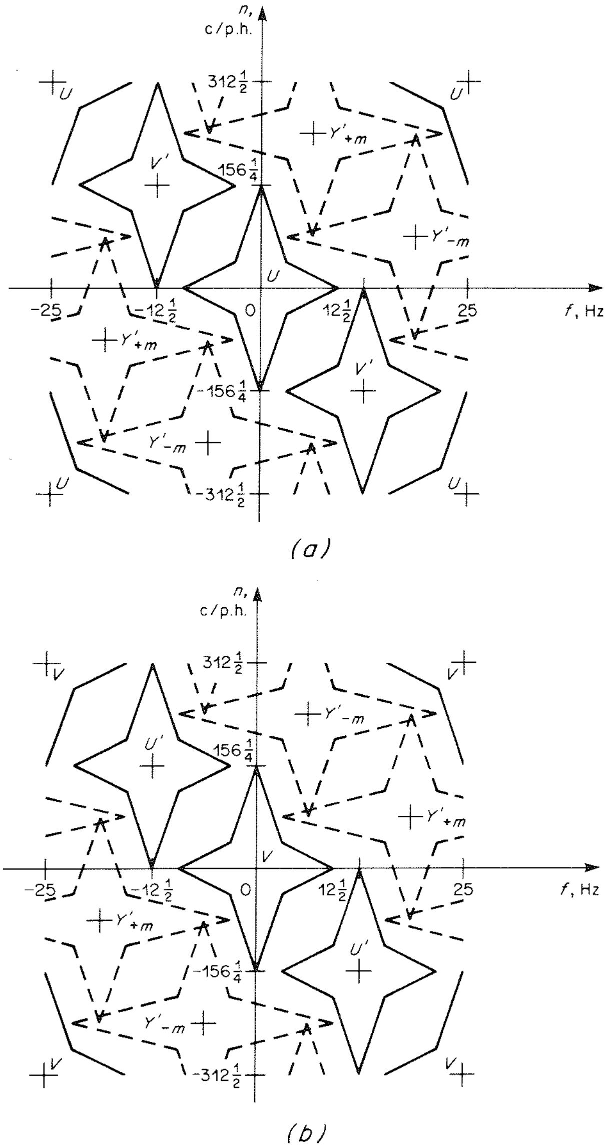


Fig. 4 - Positions of the main chrominance and luminance components in the vertical–temporal spectrum of 625/50 PAL-encoded signals after chrominance demodulation:

(a) U-channel
(b) V-channel

Y'_{+m} and Y'_{-m} denote positions of the luminance (cross-colour) components for positive and negative horizontal frequencies, respectively.

If the orthogonal phase relationship of the subcarriers is maintained, there will be no crosstalk between the two chrominance channels. However, if there is differential phase distortion or if the alignment of either the coder or decoder is inaccurate, then some crosstalk will occur. V components entering the U channel will be centred on (± 12½, ∓156¼) as shown in Fig. 4(a); U components also enter the V channel, as shown in Fig. 4(b). This accounts for the moving pattern of horizontal lines, known as Hanover bars, which is present in plain coloured areas when a phase distorted PAL signal is decoded using a simple demodulator.

3. COMB FILTERS

The conventional methods of PAL decoding, as used in domestic television receivers, make little use of the vertical and temporal offsets of the subcarrier frequency. However, comb filters can fully exploit the offsets between the true and interfering frequency components shown in Figs. 3 and 4.

When comb filters are used, it is often convenient to obtain the luminance components by first separating a chrominance signal and using this to cancel the chrominance in an appropriately delayed version of the input signal, as shown in Fig. 5(a). As the chrominance filter is common to both circuits, the resulting chrominance and luminance separation characteristics are complementary. Although simpler, the complementary circuitry restricts the choice of characteristics, so it is usually advantageous to add a second filter, as in Fig. 5(b), to allow the separation methods to be selected on their individual merits. A further rearrangement is shown in Fig. 5(c). In this case the chrominance is demodulated first and then the unwanted luminance components (cross-colour) are suppressed with baseband colour difference filters. Chrominance components in the input signal (cross-luminance) are cancelled using a remodulated version

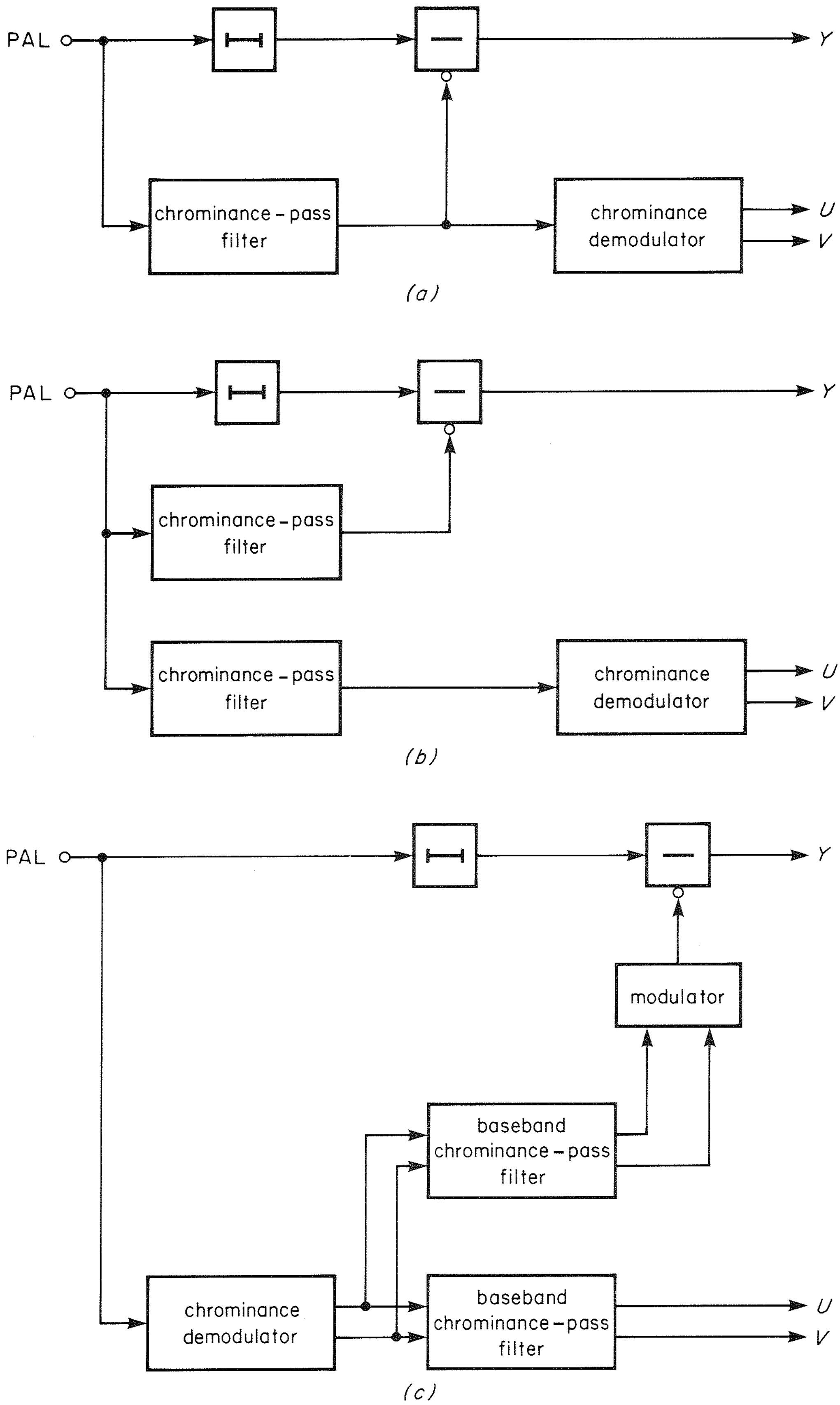


Fig. 5 - Decoder configurations:

(a) with complementary luminance and chrominance filtering
(b) with non-complementary filters
(c) with filtering applied to the baseband colour difference signals.

of the filtered colour difference signals. Whichever arrangement is used, equivalent chrominance–luminance separation performance can be achieved.

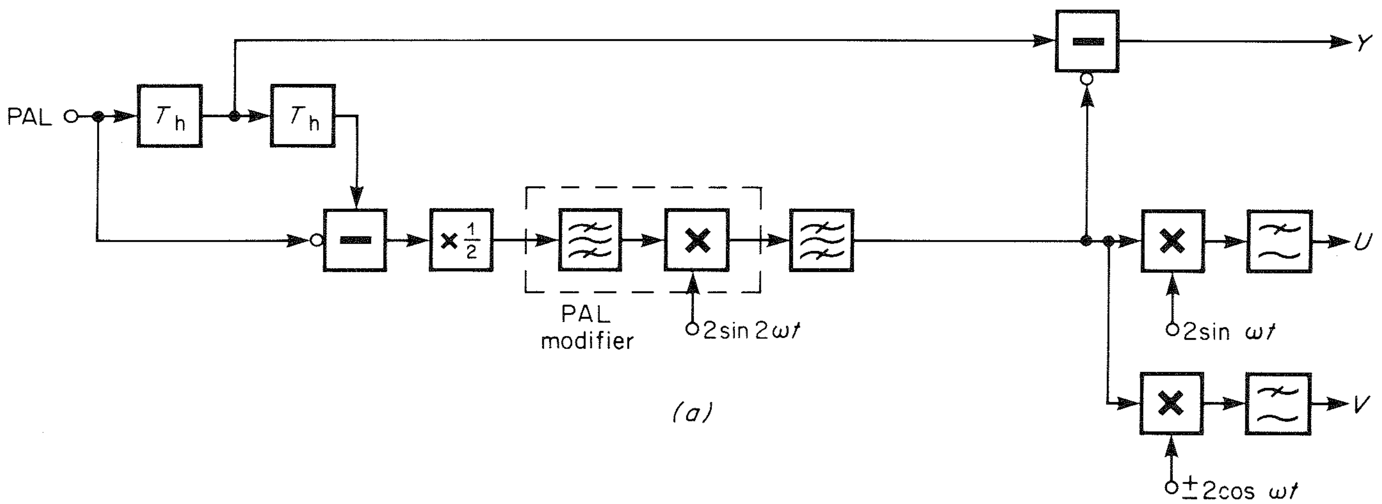
3.1 Line delay filters

In general, virtually all the simple, symmetrical comb filters fall into a relatively small number of categories, mostly depending on whether the length of delays is an odd or even number of line periods. The four principal line delay comb filter methods are shown in Fig. 6, based on the complementary arrangement of Fig. 5(a). In each case, to achieve cancellation of chrominance components at the luminance subtractor, the main contributions from the comb filter have to match the phase of the subcarriers at the centre tap of the delays. The circuits of Fig. 6 represent different methods of combining the signals from the ends of the delays to ensure that this phasing requirement is met.

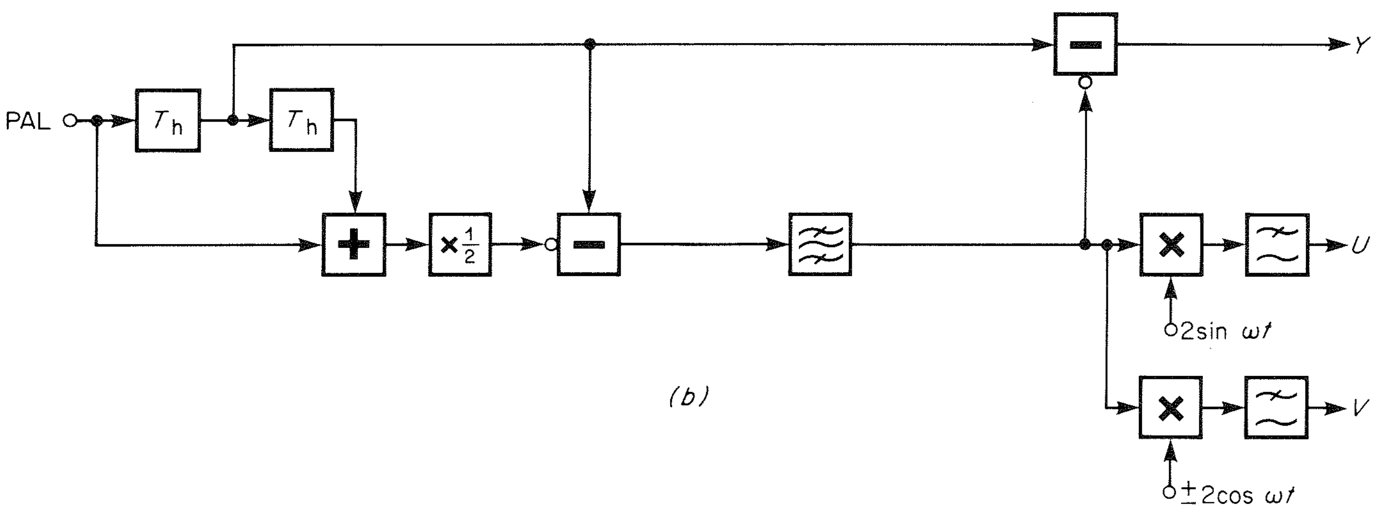
With delays of one line period, the PAL switch sense is inverted and the phase difference is approximately 90° or 270° relative to that at the centre tap. Thus the phase of both U and V subcarriers is almost exactly inverted across the two delays. One approach[8] is to combine the signals in a subtractor, as shown in Fig. 6(a). This cancels the phase inversion, producing the average of the two signals. The remaining 90° phase difference and the inversion of the PAL switch sense is removed by the PAL modifier circuit[3].

In contrast, the comb filter of Fig. 6(b) uses an adder to combine the signals from the extreme ends of the delays[9]. Because the subcarrier signals from these points are in anti-phase, most of the chrominance information is cancelled, leaving luminance. This predominantly luminance signal is then subtracted from the signal at the mid-point of the delays to leave chrominance. Since most of the incorrectly phased chrominance is suppressed by cancellation, the circuit requires no modifier nor further phase shifts, even though the original contributions are not co-phased.

A further important method of decoding using one-line delays is shown in Fig. 6(c). As shown, the Weston circuit[10] amounts to a combination of the two



(a)



(b)

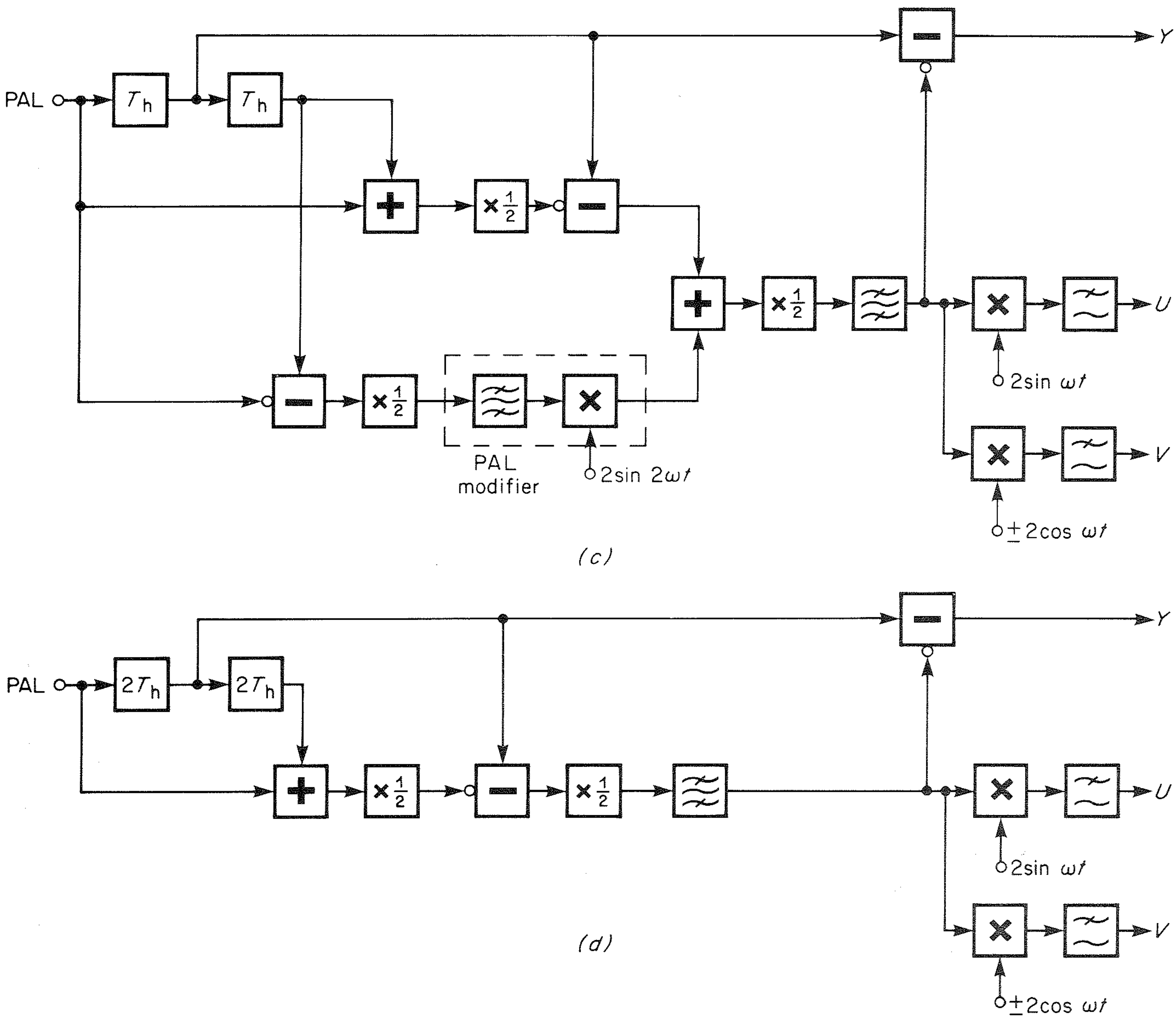


Fig. 6 - Basic line-delay comb filter arrangements for PAL decoding:
(a) two-line Roe (b) two-line cosine (c) two-line Weston (d) four-line cosine

methods shown in Figs. 6(a) and (b) with half the chrominance being contributed by each. However, in its earliest implementation, rather different circuitry was used[11].

While the circuits above demonstrate the approaches used for one-line delays, a substantially simpler method can be used when each delay is equal to two line periods[6]. Then all the contributions have a common PAL switch sense and are approximately co-phased or in anti-phase. This allows the contributions to be combined directly, as shown in Fig. 6(d).

The characteristics of these decoders have been described in more detail previously[4]. Briefly, all four circuits dramatically improve performance on line-repetitive high frequency luminance, such as the resolution bars of a test card, retaining the full 5.5 MHz resolution with no cross-colour. This improvement is obtained at the cost of introducing cross-luminance at horizontal transitions between colours and, in most cases, reducing vertical chrominance resolution. Also, the loss of resolution and the production of cross-colour reappear with diagonal luminance.

Individually, the circuits have further impairments, which do not occur with conventional decoders. With Fig. 6(a), aliased high frequency luminance is present, due to the action of the PAL modifier. When combined with the true signals, this can produce twice the normal luminance amplitude. Also, Hanover bars are not suppressed. Fig. 6(b) generates $U-V$ crosstalk at horizontal colour trans-

itions, resulting from the phase differences of the contributions used. Also, unusually large amounts of cross-colour are produced for diagonal luminance. Fig. 6(c) has luminance aliasing and $U-V$ crosstalk, but to a lesser extent than in Figs. 6(a) and (b). Fig. 6(d) provides no suppression of Hanover bars and very poor vertical chrominance resolution.

One approach to improving the circuits of Fig. 6 is to provide more line delays to allow additional contributions to be taken from further away, both up and down the field. These can be used to increase the rate of cut of the vertical frequency characteristics while still maintaining flat passband and stop-band regions. Although this results in better defined luminance and chrominance regions in the spectrum, too rapid a rate of cut tends to provoke objectionable ringing at edges in the picture, particularly on horizontal transitions between coloured areas.

3.2 Extension to field- and picture-based filters

As the circuits of Fig. 6 depend primarily on the subcarrier phase relationship at the ends of the line delays, other delay lengths can be used, provided that any phase differences that this incurs are taken into account. For example, the phase and PAL switch sense across a picture delay (625 lines) is almost exactly the same as that for a 1-line delay. Thus, picture delays can be substituted directly in the comb filters of Figs. 6(a), (b) and (c), or 2-picture delays could be used in Fig. 6(d). Whereas with line delays, the benefits were confined to line-repetitive signals, with picture delays the advantages extend to all spatial frequencies. Because of this, still pictures can be decoded with full spatial resolution and without any significant cross-effects. However, the impairments arising for vertical detail with the line delays are exchanged for similar types of impairment occurring instead on moving areas of picture.

Another alternative is to use 313-line delays, which have a 180° phase shift relative to that across a 1-line delay. Compensation for this can be made by inverting the contributions from the ends of the delays, for example by altering the modifier phase in Fig. 6(a) or by changing the lower subtractor to an adder in Fig. 6(b). The performance then falls between that of the corresponding line-based and picture-based versions, having better static resolution and reduced cross-effects compared with the line-based versions. However, the 313-line decoders have impairments to both vertical detail and movement, although in each case the extent of each impairment is less than that for the corresponding line- or picture-based version.

With 312-line delays, the PAL-switch sense is the same as with 2-line delays and the relative phases are almost identical, so the circuit of Fig. 6(d) can be used directly[6]. This overcomes the poor vertical chrominance resolution of the 2-line circuit, although Hanover bars remain unsuppressed.*

The change of frequency characteristics resulting from changing the delay lengths in the circuits of Fig. 6 is most easily visualised in the two-dimensional vertical–temporal frequency plane. Fig. 7 shows the areas of the spectrum removed by chrominance-pass line-, field- and picture-delay comb filters, with the boundary between the shaded and unshaded portions marking the −6 dB contour. The detail of the characteristic varies according to the particular filter arrangement used; the characteristics of Figs. 7(a), (c) and (d) correspond to the circuit of Fig. 6(a) with appropriate delays in each case, while the characteristic of Fig. 7(b) results from the circuit of Fig. 6(d) with 312-line field delays.

With line delays, the characteristics are purely a function of vertical frequency. So, in Fig. 7(a), the areas retained run parallel to the temporal frequency axis, to include the subcarrier positions at (6¼, 234⅜), (18¾, 78⅛), etc., and to reject the main luminance components centred on the origin. Clearly, a symmetrical structure like this limits the vertical chrominance resolution that can be obtained to less than 78⅛ c/p.h. However, more vertical detail can be retained with the circuits of Figs. 6(b) and (c), by making the filters asymmetrical relative to the subcarrier frequency. Thus, more resolution can be obtained from the upper sideband, but this is accompanied by $U-V$ crosstalk because the loss of sideband symmetry destroys the phase orthogonality of the subcarriers. The crosstalk causes horizontal edges of brightly coloured areas to flash with a frequency of 12½ Hz.

Field delays of 312 and 313 lines produce the two oppositely sensed diagonal characteristics shown in Figs. 7(b) and 7(c), respectively. However, the filter using 312-line delays is better suited to the relative positions of the chrominance and luminance energy centres. This allows a coarser pitch of characteristic to be used, which retains more of the wanted chrominance while rejecting more of the unwanted luminance. Accordingly this filter gives a good balance between resolution and cross-effects for both still and moving pictures.

With picture delays, the response is only a function of temporal frequency, as shown in Fig. 7(d). For still pictures, all the signal energy is concentrated along lines parallel to the vertical axis; luminance

* A fully digital production PAL decoder using 312-line delays was produced by BBC Designs Department and first demonstrated in September 1984. Currently ten units to this design are either already installed or being prepared for service in the BBC.

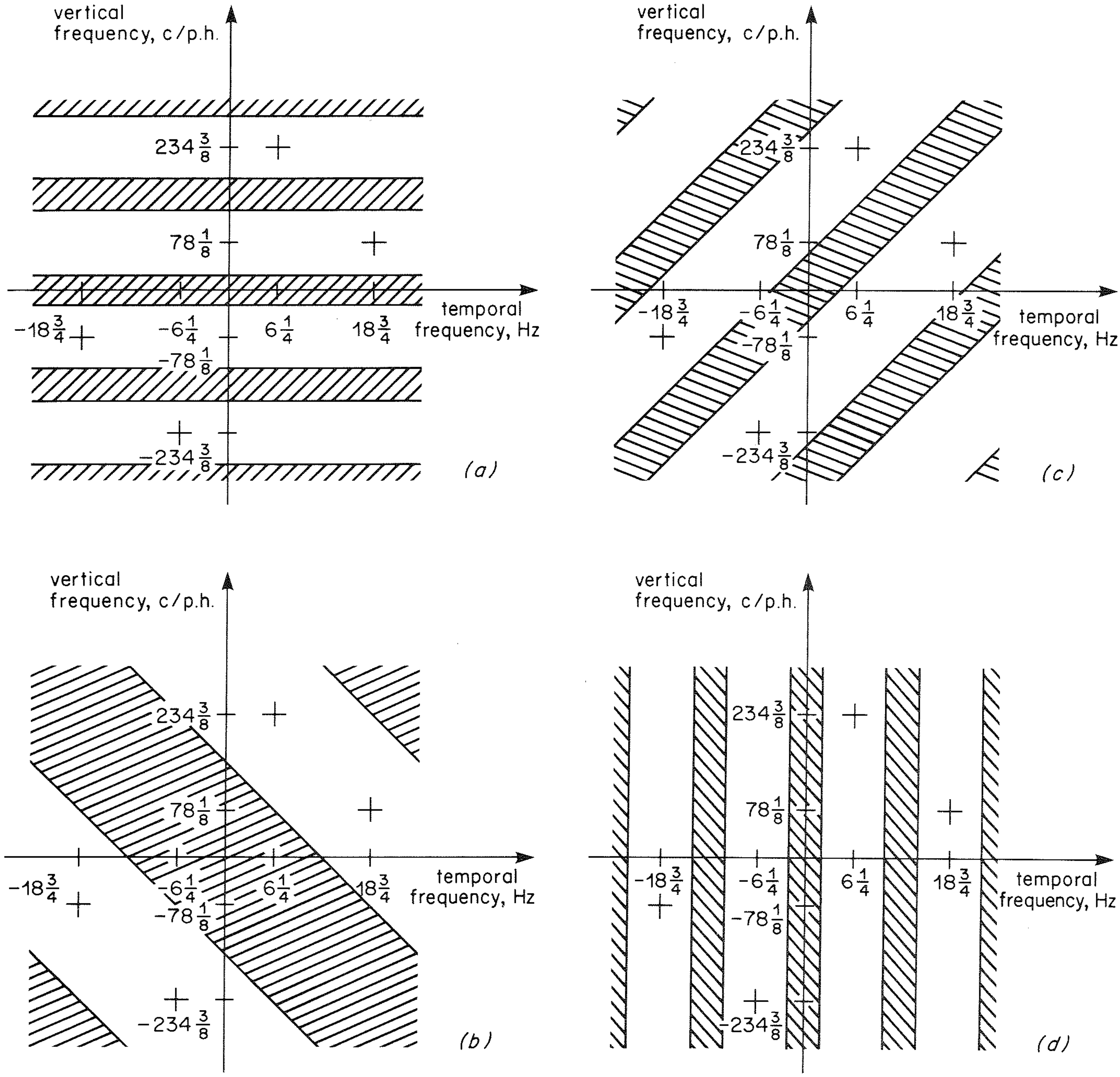


Fig. 7 - The vertical—temporal frequency characteristics of line-, field- and picture-delay comb filters for chrominance—luminance separation:

(a) 1-line delays (b) 312-line delays (c) 313-line delays (d) 625-line delays

Hatched areas denote the stop-bands of chrominance-pass filters

energy is concentrated at 0 and ±25 Hz, while chrominance energy is located at ±6¼ and ±18¾ Hz. It can be seen from the diagram, therefore, that the 625-line comb filter can give perfect separation of luminance and chrominance. However, for moving pictures, similar limits apply to the temporal response as occur in the vertical response of the line-based filters. This causes movement to become blurred and cross-luminance and cross-colour to return for temporal frequencies in the 6¼ Hz region.

Of all the field- and picture-based methods, the 312-line field-based method and the 625-line Weston method are the most promising. However, both have serious drawbacks. The 312-line method fails to suppress Hanover bars, while the 625-line method can produce serious impairments on rapid movement. In addition, in common with other methods using PAL modifiers, its performance is also affected by differential phase distortion. This causes the signals derived by a phase shift of chrominance from adjacent lines to be

no longer in the correct phase to cancel the subcarrier on oppositely-switched lines. As the distortion increases, there is a rapid increase in the level of unsuppressed subcarrier in uniformly coloured areas. When the signals are subsequently recoded, the unsuppressed subcarrier from the original encoding could interfere to produce hue errors at the final decoder.

3.3 Multi-tap filters

Additional delays of the same length could be used to produce sharper frequency characteristics, as mentioned earlier for the line-based filters, but this would tend to result in temporal ringing. This appears as superimposed multiple images on moving parts of the picture. However, it is sometimes advantageous to combine different lengths of delay within the same filter. Combination before demodulation is complicated by the different phases and PAL-switch senses of the contributions. So it is easier, conceptually, to consider the weights of the different contributions for filtering after the demodulator, such as with the arrangement of Fig. 5(c). A suitable low-pass vertical—temporal characteristic can then be produced simply by averaging a number of positive contributions.

For example, with a 312-line decoder, Hanover bars could be suppressed by adding contributions from oppositely switched lines, to make the totals from odd- and even-numbered lines equal. Fig. 8 shows the PAL-switch sense of the surrounding lines relative to a line, ℓ, at the centre tap of the filter. The addition of $\ell \pm 313$-line contributions would suppress the bars, but leads to an unsatisfactory characteristic with large negative responses. Using both 1-line and 313-line additional contributions, as shown in Fig. 9(a), produces a more satisfactory response, shown in Fig. 9(b). Alternatively, adding 625-line contributions, as in Fig. 10(a), maintains the suppression of Hanover bars while producing a useful improvement in static resolution for vertical chrominance by eliminating the zero line at 156 c/p.h., as shown in Fig. 10(b). It should be noted that the simple binary fractional weights chosen in Figs. 9 and 10 can be implemented by shifting the significance of the binary digits and so result in simpler hardware than those requiring full multipliers.

Although the choice of filter coefficients after demodulation is simpler in concept, in practice filtering before demodulation usually results in simpler hardware. Then it is necessary for the contribution weights to take account of the subcarrier phase on each line relative to the demodulator reference phase. As this advances in multiples of approximately 90°, this requires that some of the contributions are inverted and some are passed through a 90° phase shift network operating over the chrominance band.

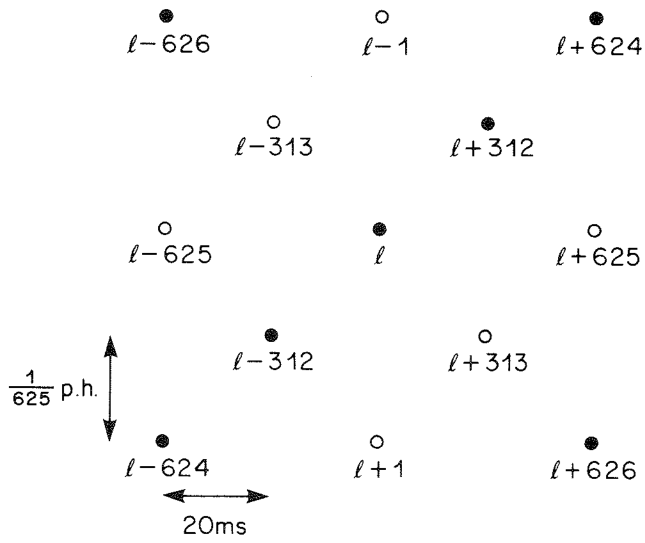


Fig. 8 - The PAL-switch sense of lines in a 625/50 interlaced scan relative to a line, ℓ.

● Lines with the same PAL switch sense as line ℓ.
○ Lines with the opposite PAL switch sense to line ℓ.

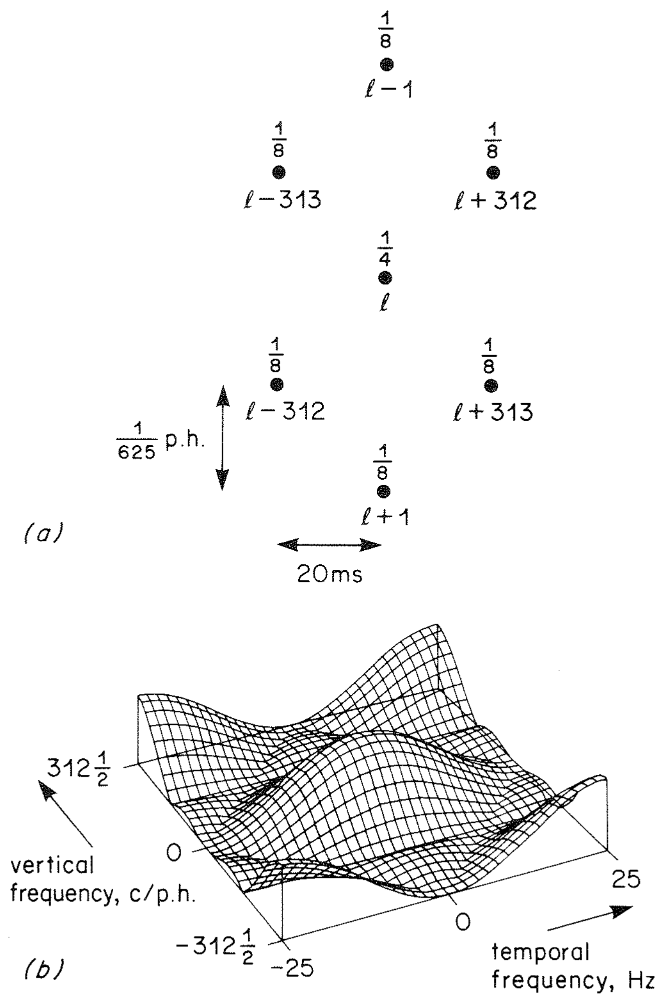


Fig. 9 - A decoder using dual 1-, 312- and 313-line contributions:

(a) contribution weights
(b) frequency characteristic

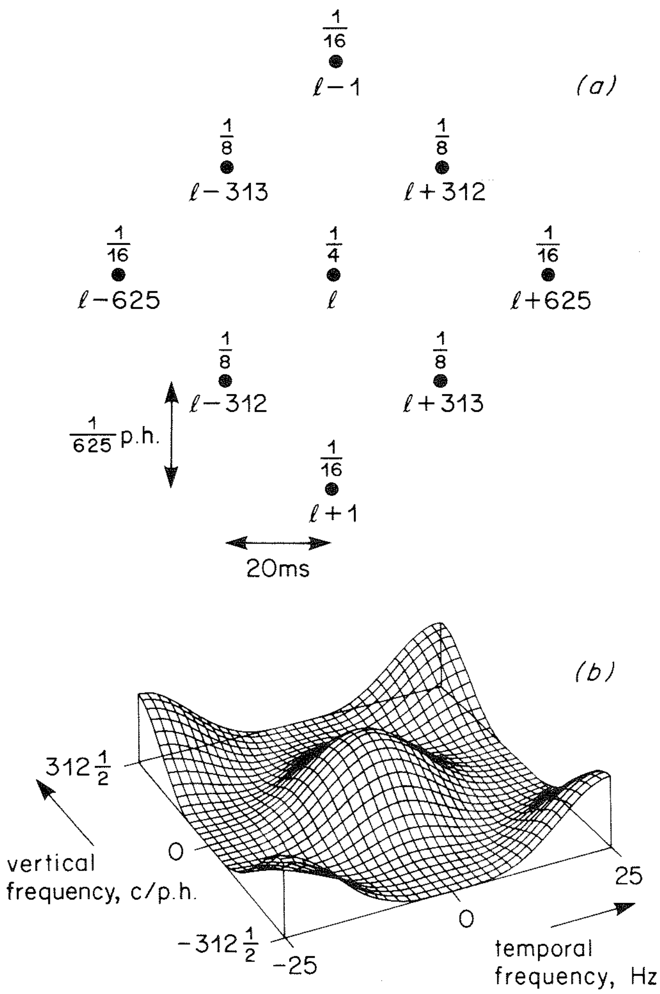


Fig. 10 - A decoder using dual 1-, 312-, 313- and 625-line contributions (4-field decoder):

(a) contribution weights
(b) frequency characteristic

This phase shift can be obtained using a transversal filter with an anti-symmetrical impulse response[3]. To take account of the PAL switch, some contributions in the *V* channel must be inverted, so separate feeds are needed to the *U* and *V* demodulators.

In principle, the same filter could also define the luminance response, with the required PAL-switch inversions being obtained from a PAL modifier. This would produce complementary luminance and chrominance signals at the decoder outputs. The disadvantage of this approach is that any differential phase distortion in the PAL signal would result in unsuppressed subcarrier appearing in the luminance output.

It is preferable, therefore, to use the 'pseudo-complementary' filter obtained by inverting all the contribution weights of the baseband chrominance low-pass filter except the centre term, which is subtracted from unity. When this filter is applied directly to the input signal and the region of combing is defined by a high-pass filter, the resulting signal can be subtracted from an appropriately delayed version of the composite input signal to produce luminance. This method of filtering does not require a PAL modifier and so avoids leaving areas of unsuppressed subcarrier when the input is affected by differential phase distortion. The contributions for dual 1-, 312-, 313-line and dual 1-, 312-, 313-, 625-line luminance filters are shown in Fig. 11. This maintains the advantage of using binary fractions for most of the contributions, so that the weighting factors can be implemented by bit-shifting.

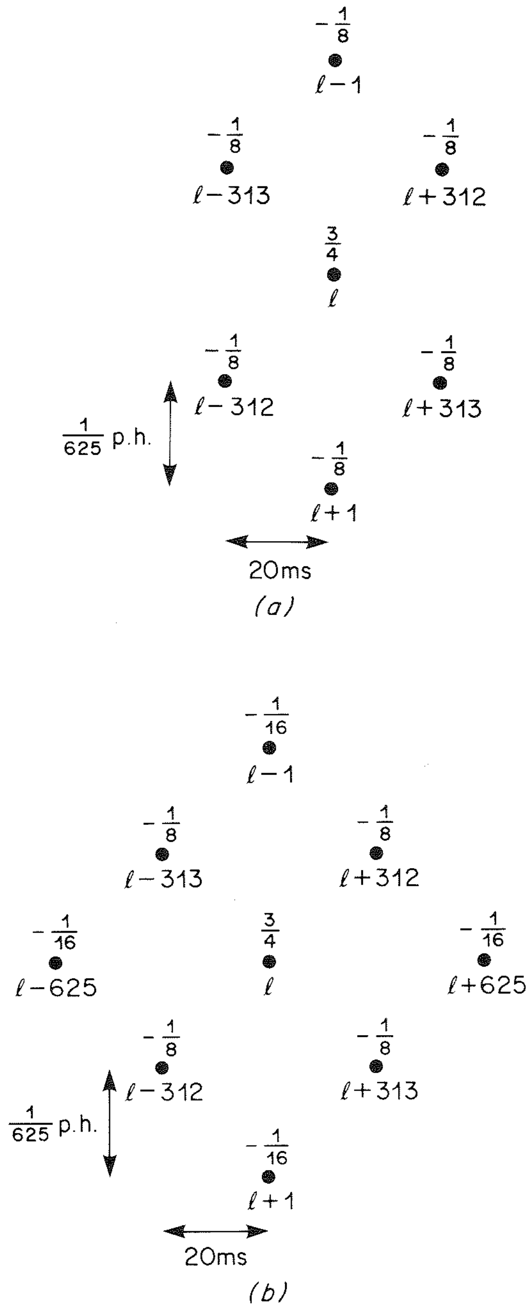


Fig. 11 - Contribution weights for 'pseudo-complementary' luminance:

(a) the 1-, 312-, 313-line decoder
(b) the 1-, 312-, 313-, 625-line decoder

When chrominance filtering before demodulation is used with 'pseudo-complementary' luminance, the delays, the weighting circuits and some of the adders can be made common to both filters. Such an arrangement is shown in Fig. 12 for the 1-, 312-, 313-, 625-line decoder. A similar circuit could be used for the 1-, 312-, 313-line decoder. However, in this case, the luminance circuit of a dual 312-line decoder might be preferable and the modifications to provide this instead are straightforward. This would reduce the loss of diagonal luminance and would make the cross-luminance less noticeable.

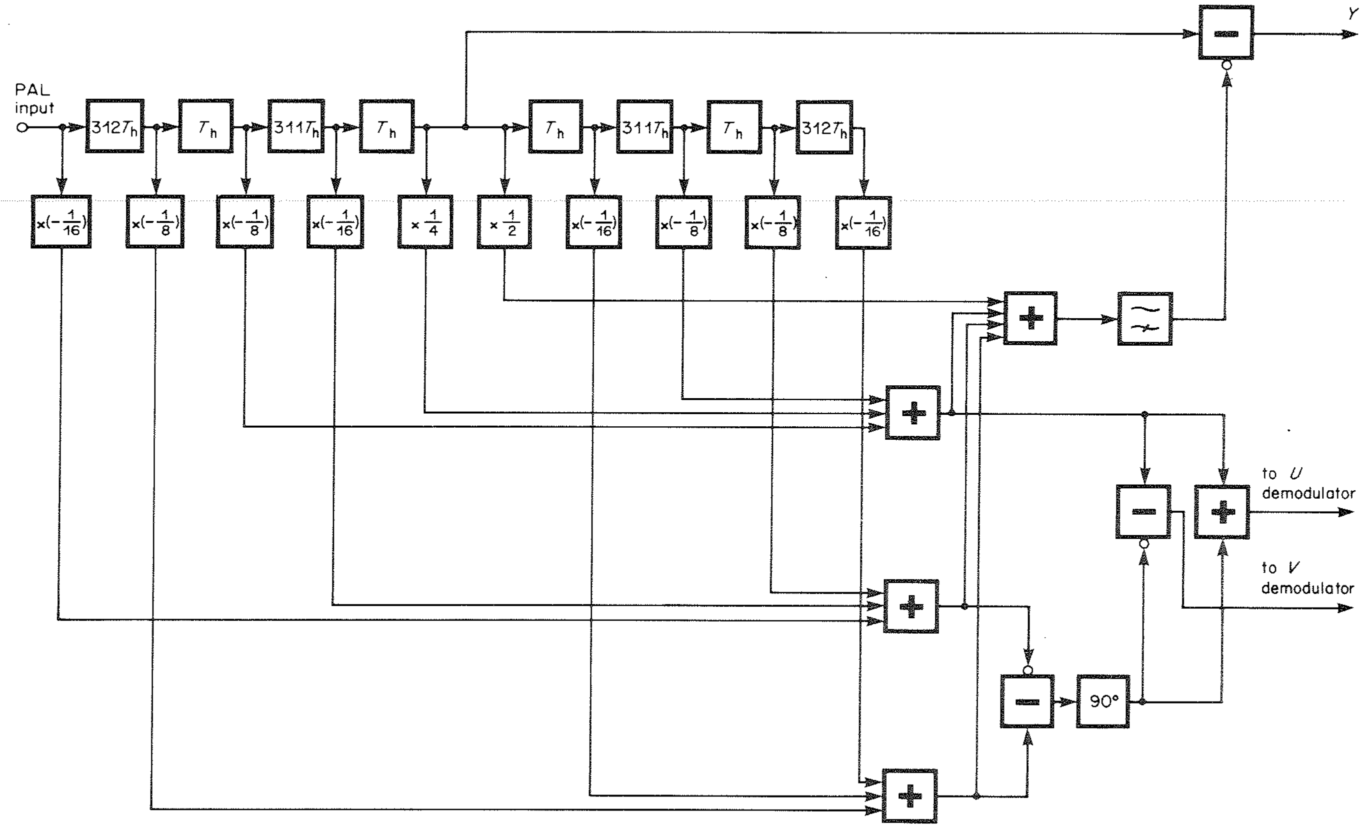


Fig. 12 - Combined luminance and chrominance filtering for a dual 1-, 312-, 313-, 625-line (4-field) decoder.

4. FILTER OPTIMISATION

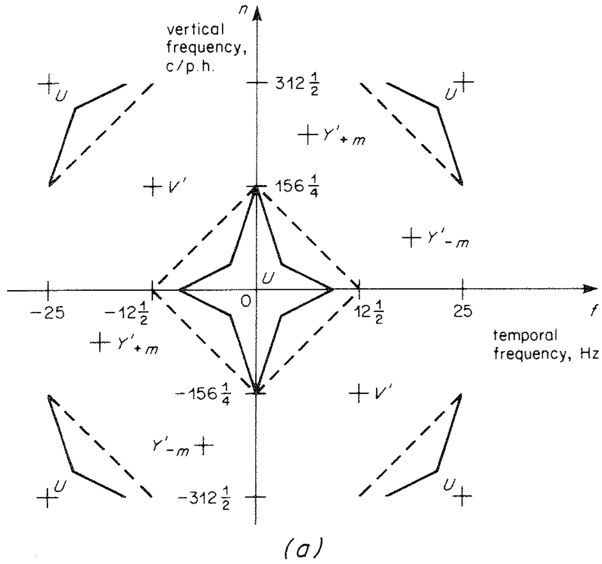
The main factor influencing the design of the simple comb filters described in Sections 3.1 and 3.2 has been the need to accommodate the complicated line-to-line relationships of the PAL colour signal. Thus, the early methods reflected the characteristics that could be achieved easily, rather than those that approached an 'ideal' in spectral terms. Even the rather more sophisticated multi-tap combs of Section 3.3 were constrained to use relatively simple combinations of weighting coefficients, those selected being the ones that provided broadly appropriate frequency characteristics.

The relative positions of the wanted and unwanted components in the demodulated chrominance spectra of Fig. 4 call for a filter approximating to the characteristics shown in Fig. 13, primarily retaining the lower temporal and vertical frequencies, but with more response along the axes. This shape suppresses all the centres of the unwanted chrominance components adequately. Also, a similar filtering effect can be applied to the spectrum of Fig. 3 to separate the high frequency luminance. The problem then arises as to how such characteristics can be designed and optimised in an efficient manner.

4.1 Experimental decoder hardware

It is apparent that a filter characteristic suppressing the unwanted components as shown in Fig. 13 requires a wide aperture and a large number of taps. Also, optimisation of the response requires a high degree of flexibility in setting the tap delay lengths and the coefficient weighting factors. Hardware based on the block diagram of Fig. 14 has been developed to provide this and includes separate filters for luminance and chrominance so that the individual responses can be optimised separately. For versatility, the luminance filtering effect is obtained by applying a baseband chrominance comb filter to the demodulated signals and then remodulating in the same subcarrier phase. This avoids having to take account of the subcarrier reference phase at each of the taps and to modify its contribution accordingly. After remodulation, the separated chrominance signal is then subtracted from the input composite signal, appropriately delayed in order to cancel the chrominance

components, thus leaving luminance. The filter taps and coefficients are set by loading data from a computer disk store under the control of a microcomputer. This provides virtually instant push-button loading of any of a wide variety of filter characteristics to allow rapid comparisons of alternative responses.



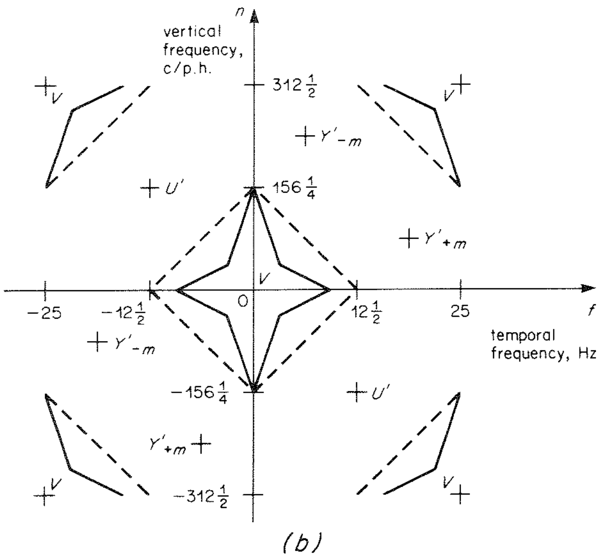


Fig. 13 - Suppression of unwanted components in the demodulated chrominance signals using a filter characteristic with reduced response to vertical and temporal frequencies:

(a) for the *U*-channel
(b) for the *V*-channel

Y'_{+m} and Y'_{-m} denote the positions of the luminance (cross-colour) components for positive and negative horizontal frequencies, respectively.

The chrominance comb filters all have delays arranged as shown in Fig. 15. The pairs of taps are added together and each of the resulting signals is taken to a programmable multiplier, thus providing the 41-tap array of contributions shown in Fig. 16. Each filter contains eight field delays and up to 36 line delays, and it is unrealistic, at least at present, to envisage decoders using more storage than this. However, the cost of a dedicated decoder would be substantially less because there would be no requirement to vary the tap positions and coefficient values.

4.2 Filter design techniques

The synthesis of two-dimensional frequency characteristics conforming to the constraints of Fig. 13 is particularly difficult because the diamond shape required is non-variables-separable. The non-rectangular array of line positions in the interlaced scan is an added complication. If the array of lines were rectangular and a rectangular response were required, the characteristic could be calculated as two variables-separable one-dimensional responses.

It is possible to proceed with this approach by rotating the axes of the frequency characteristic by 45° to make the response rectangular and variables-separable. Also this would make the array of line positions in the interlaced scan correspond to the orthogonal structure of a sequential scan. However, from a practical viewpoint, the resulting array of contributions required would not be a good match to the array of storage shown in Fig. 15. Because line delays are cheaper than field delays and a repetitive structure is easier to construct, the contributions provided by the store tend to produce a rectangular array of contributions on the original axes, as shown in Fig. 16. Also there is no justification for treating vertical and temporal frequencies in the same way, which would be a necessary consequence of this approach.

A preferable alternative is to treat the available array of lines as being rectangular by adding the missing line positions of the corresponding sequential scan. This results in no loss of generality. If the frequency characteristic is chosen to ensure that coefficient values at the added line positions are always zero, the remaining coefficients can then be applied immediately to an interlaced signal application.

A commonly used method of filter design is to calculate the coefficients for an ideal characteristic and to use an approximation by 'windowing' the coefficients to match the available contributions. In this case, because the number of taps in each dimension is relatively small, the method is unsuitable because the choice of window function virtually determines the shape of the response. Instead, it is much better to calculate the frequency characteristic by a method which automatically includes the filter size limitation. Specifically, the overall dimensions of the filter aperture determine the spacing of points at which the frequency characteristic can be specified.

The basis for such a method is demonstrated for a one-dimensional case in Figs. 17 and 18. The

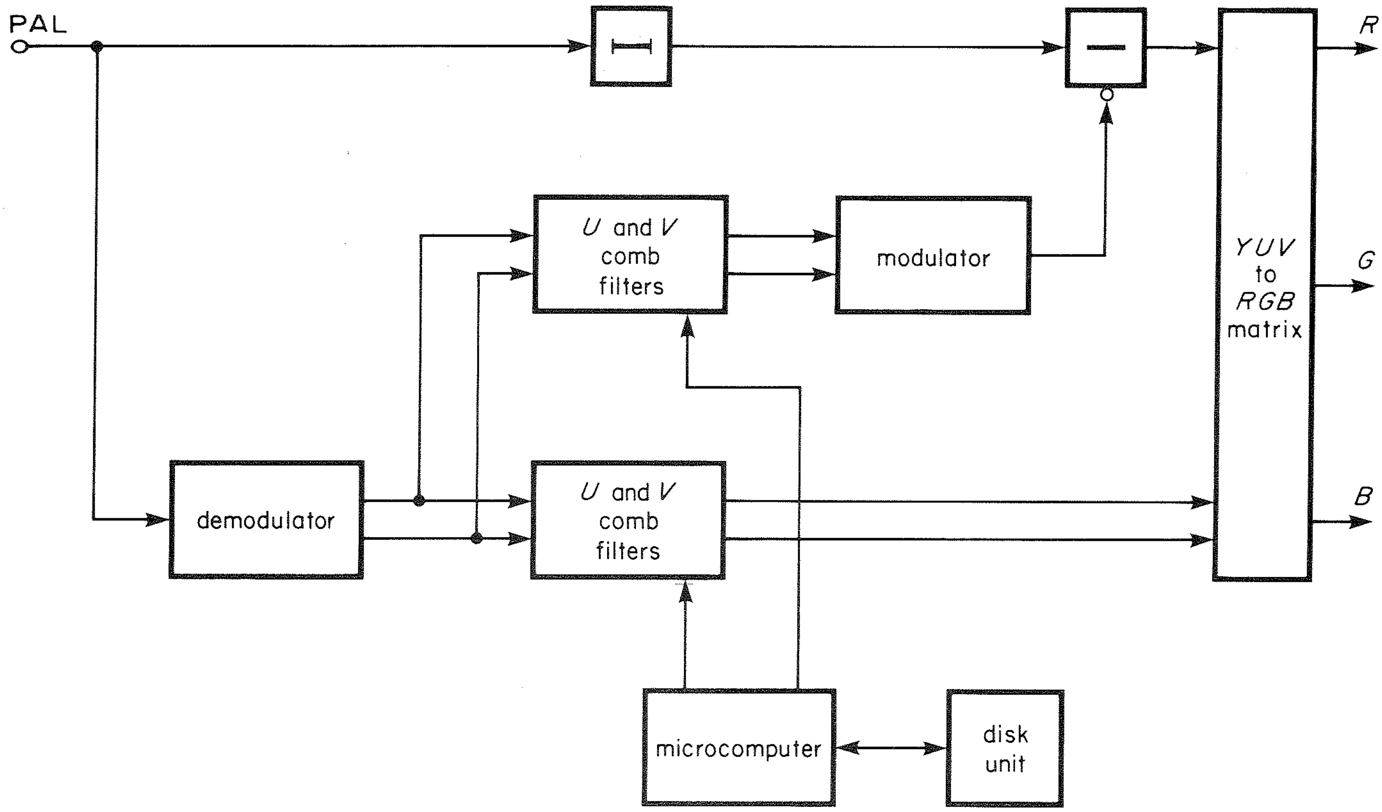


Fig. 14 - A versatile PAL decoder configuration used for comparing vertical—temporal filtering methods.

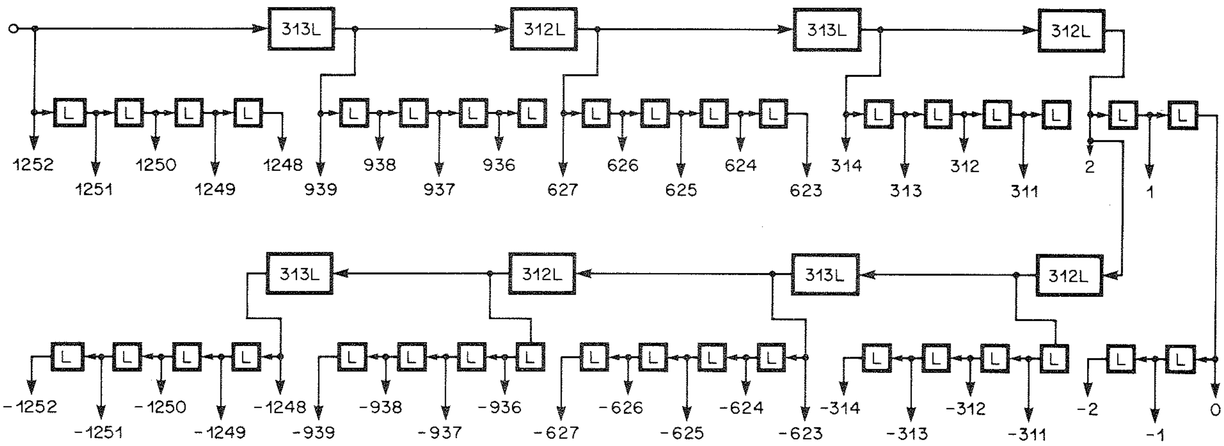


Fig. 15 - The arrangement of line and field delay elements used in each comb filter of the PAL decoder of Fig. 14.

discrete, aperiodic impulse response of the filter shown in Fig. 17(a) corresponds to the continuous, periodic frequency response of the filter shown in Fig. 18(a). However, Fig. 17(a) can be considered as the result of multiplying together the discrete periodic impulse response of Fig. 17(c) and the rectangular pulse of width equal to the filter aperture, shown in Fig. 17(b). The corresponding operation in the frequency domain consists of convolving the discrete, periodic spectrum of Fig. 18(c) with the sinc function of Fig. 18(b). As the sinc function value is zero at all other impulse positions, the continuous characteristic (Fig. 18(a)) produced by this convolution has the same values as the discrete impulses at the positions shown in Fig. 18(c). Thus, the impulse values of Fig. 18(c) can be set independently to produce the desired continuous characteristic, consistent with the resolution of the set frequency points. If a wider filter aperture is used, the spacing of the set points is reduced, so allowing a faster rate of cut to be achieved.

As Figs. 17(c) and 18(c) are both discrete and periodic, they are related in the two directions by the Discrete Fourier Transform and its inverse. So the impulse response values of Fig. 17(c) can be calculated from the set values of Fig. 18(c). If there are shared

values at the edge of the repeat period in Fig. 18(c), these have to be halved to take account of their effect in each cycle period. Similarly, shared values at the edge of the cycle period in Fig. 17(c) have to be halved to produce the coefficient pattern of the filter shown in Fig. 17(a).

The two-dimensional case can be simplified by assuming four-quadrant symmetry so that the pattern of set points then appears as shown in Fig. 19(a). The arrangement of filter taps of Fig. 15 allows the response values to be set at intervals of 6¼ Hz and 78⅛ c/p.h., thus providing points at the centres of the unwanted spectra. Any smaller aperture filter than Fig. 15 would not allow this important feature to be obtained. However, because the set points relate to a sequential scanning standard, only approximately half the points can be set independently. To take account of interlaced scanning, all the pairs of points centred on (12½, 156¼) have to have equal values. Then, when the frequency values are transformed to produce the coefficient pattern of Fig. 19(b), zero coefficient values are produced at all the positions where no lines exist. As in the one-dimensional case, edge values have to be shared, so values on the 25 Hz or 312½ c/p.h. lines are halved and the (25, 312½) value reduced to one quarter. A similar weighting pattern is applied to the converted values to obtain the correct filter coefficients.

4.3 Choice of coefficients

The symmetry requirement of interlaced scanning reduces the number of independently set frequencies from 25 to 13 in the quadrant. Of these, the origin must have a value of unity and the main centre of cross-effects (18¾, 78⅛) zero response. In addition,

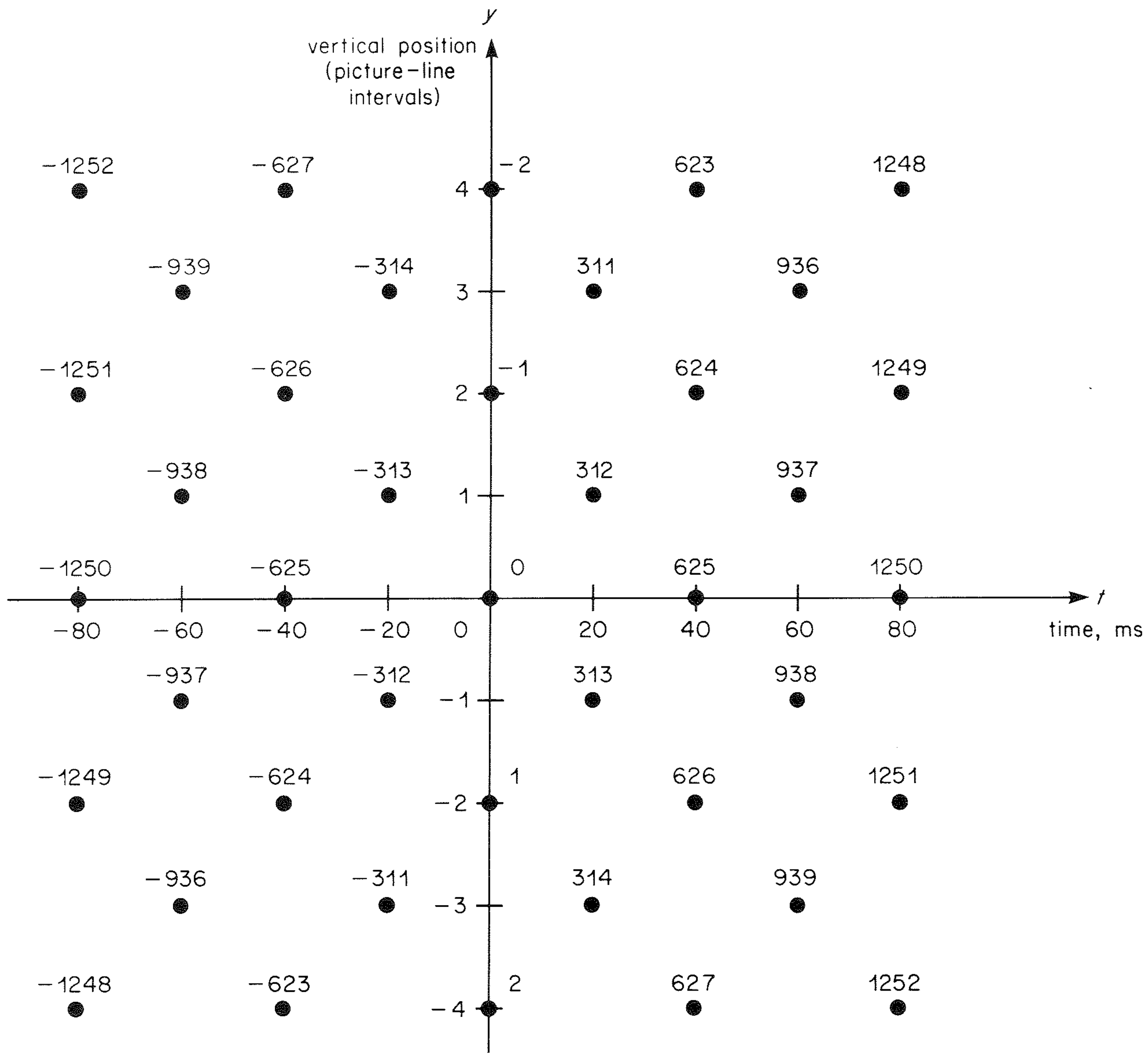


Fig. 16 - The array of contributions available in the vertical–temporal filters of Fig. 14.

to suppress $U\!-\!V$ crosstalk in chrominance signals requires a zero at (12½, 156¼). Also, it should be noted that the response value cannot change abruptly from one set point to the adjacent ones without causing large overshoots in the continuous characteristic between the set frequencies. A reasonably slow roll-off characteristic is required anyway to avoid strong multiple images of moving objects, which result from ringing in the time domain.

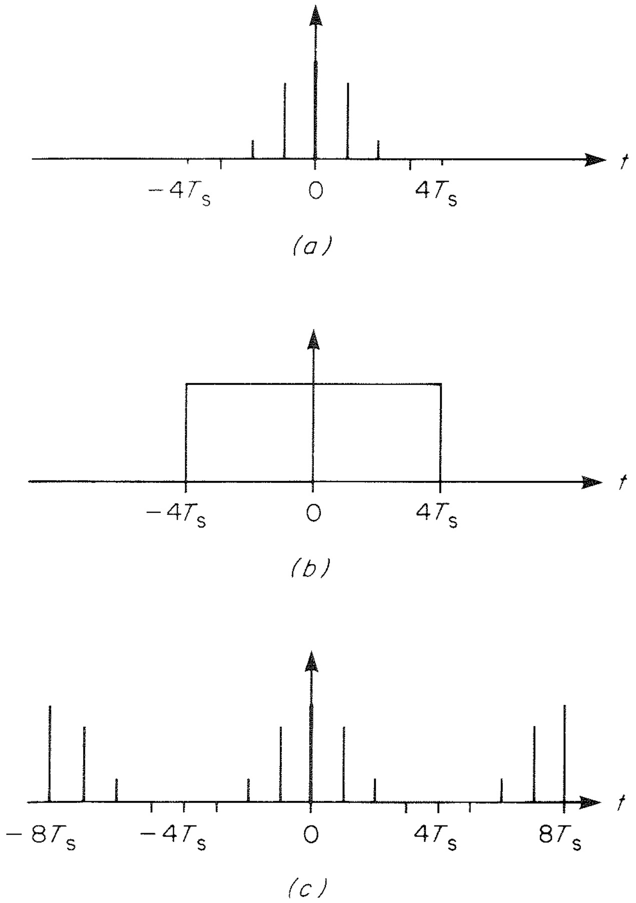


Fig. 17 - The constraint of limited filter width in the time domain:

(a) the discrete, aperiodic impulse response of a transversal filter may be considered as (b) the product of a block pulse equal to the aperture width of the filter and (c) a discrete, periodic impulse response.

Because of these constraints, the range of different filters that can be produced is relatively small and the design becomes a simple compromise between resolution loss and suppression of cross-effects. However, because the temporal components of colour signals are limited by their lower horizontal bandwidth, quite narrow temporal bandwidths can be used without serious impairment. Also, as the filtering effect in luminance is limited to the high horizontal frequencies, narrow temporal bandwidths can again be used with effects not unlike extended camera integration.

Consideration of these factors, particularly with a view to exploiting the reduction of temporal chrominance bandwidth, led to the selection of the values shown in Fig. 20. The set points in the chrominance filter, Fig. 20(a), were chosen first by setting the origin to unity and the centres of cross-colour and $U\!-\!V$ crosstalk to zero. To keep the amount of cross-colour on stationary pictures at a low level, the temporal response was reduced rapidly to

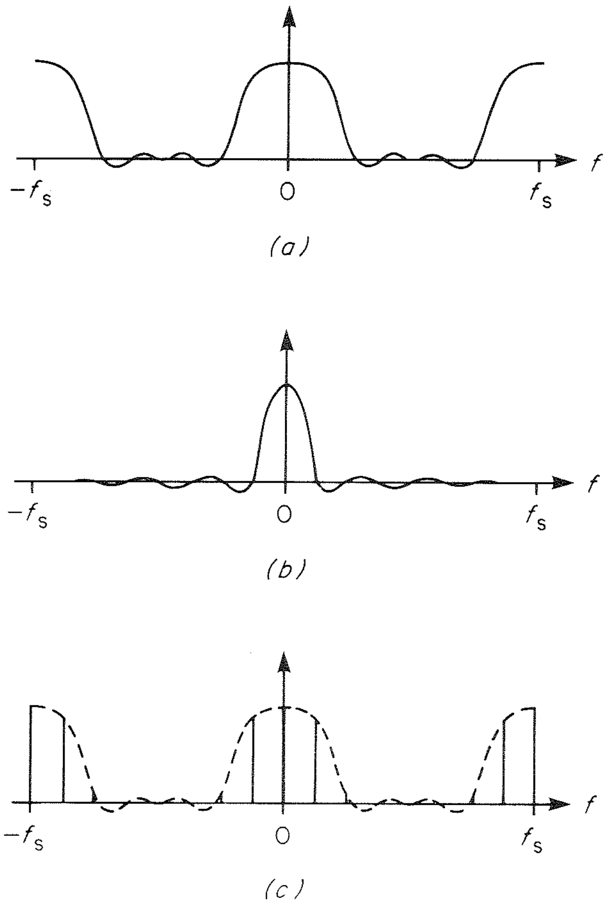


Fig. 18 - Spectra corresponding to the waveforms of Fig. 17:

(a) the continuous periodic frequency characteristic of a transversal filter can be obtained by convolving (b) the sinc function and (c) the series of weighted impulse values representing points on the response of (a).

0.2 at 6¼ Hz, a value that virtually ensures that cross-colour is negligible in normal pictures. Cross-colour can still be seen, however, on test patterns for diagonal luminance, such as a zone plate. Keeping a finite response at this point avoids overshoots in the temporal characteristic and reduces the degree of blurring on moving chrominance. The points defining the vertical response, on the vertical frequency axis, were chosen as a compromise between static vertical chrominance resolution and cross-colour on moving objects. Originally a raised-cosine characteristic was tried, falling to zero at 312½ c/p.h., however, the

response at 156 c/p.h. was reduced slightly to prevent overshoots in the characteristic in the (10, 156) region. This maintained a relatively high level of vertical resolution, substantially greater than that of a conventional delay line circuit. On the other hand, cross-colour tended to return on moving high frequency luminance, although this was judged to be a reasonable compromise.

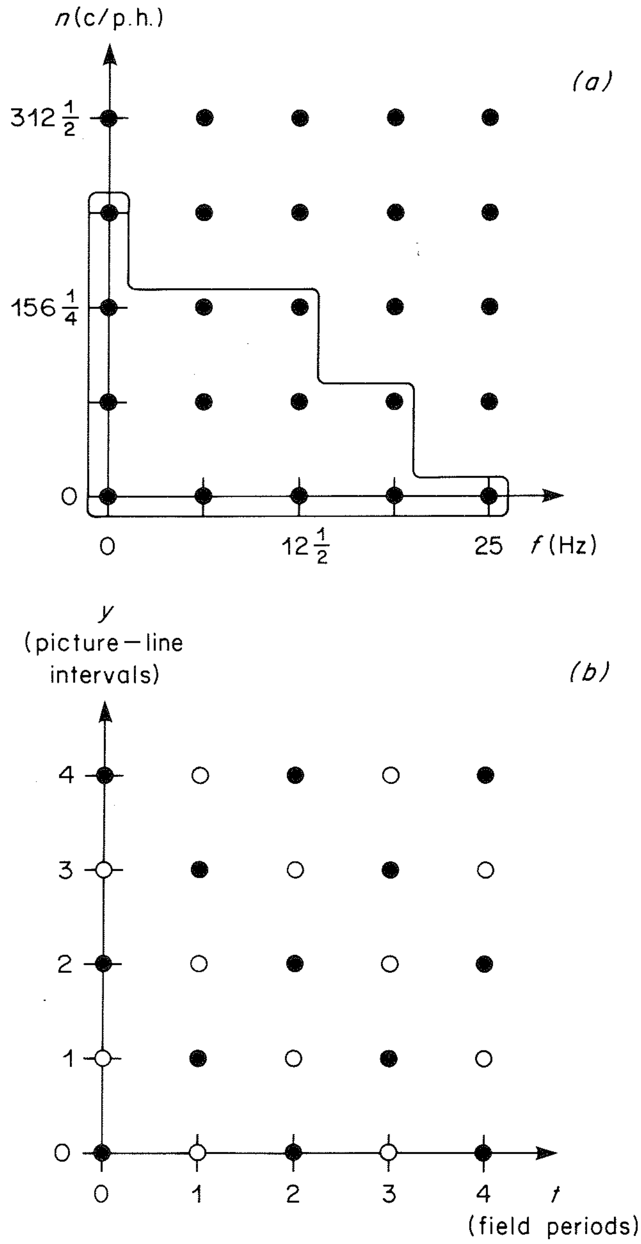


Fig. 19 - Specification of coefficients for 2-dimensional filters:

(a) the pattern of specification points in one quadrant of the vertical–temporal spectrum
(b) the corresponding array of contribution points in the time domain.

Choosing independently only the thirteen values in the outline in (a), obtaining the remainder by symmetry about (12½, 156¼), makes alternate values zero in (b) as required for an interlaced scan.

O represents zero coefficient values

The corresponding values chosen for the luminance comb filter are shown in Fig. 20(b). As this filter is designed to separate modulated chrominance for use in cancelling subcarrier components in the input signal, the response at the subcarrier positions is unity and that at the origin is zero. Residual subcarrier on horizontal chrominance transitions is kept at a low level by specifying a raised-cosine characteristic vertically, falling gradually from the subcarrier positions. A rather more abrupt reduction of the response is used in the temporal direction, in an attempt to preserve more static luminance resolution. Nevertheless, limiting the fall to 0.5 at (0, 312½) results in a noticeable return of subcarrier on moving chrominance edges. High values are maintained in the (12½, 156¼) region to improve the suppression of subcarrier sidebands at the expense of relatively unimportant moving high frequency luminance components.

Conversion of the fixed-point values shown in Fig. 20, using the method described in the previous sub-section, results in the frequency characteristics shown in Fig. 21 and the coefficient values shown in Table 1. The implementation of such an 8-field decoder and using the array of storage modules shown in Fig. 15 would require the contributions to be weighted and combined using the circuitry of Fig. 22. Some simplification could be made, however, by eliminating very small coefficients and adjusting others to compensate, without significantly altering the performance.

(a)

c/ph \ Hz	0	6·25	12·5	18·75	25
$312\frac{1}{2}$	0·0	0·0	0·0	0·2	1·0
$234\frac{3}{8}$	0·1	0·0	0·0	0·15	0·9
$156\frac{1}{4}$	0·4	0·05	0·0	0·05	0·4
$78\frac{1}{8}$	0·9	0·15	0·0	0·0	0·1
0	1·0	0·2	0·0	0·0	0·0

(b)

c/ph \ Hz	0	6·25	12·5	18·75	25
$312\frac{1}{2}$	0·5	0·854	0·5	0·146	0·0
$234\frac{3}{8}$	0·427	1·0	0·854	0·5	0·073
$156\frac{1}{4}$	0·25	0·854	1·0	0·854	0·25
$78\frac{1}{8}$	0·073	0·5	0·854	1·0	0·427
0	0·0	0·146	0·5	0·854	0·5

Fig. 20 - Values of points set in the vertical–temporal frequency domain to design a decoder using the contributions shown in Fig. 16:

(a) chrominance
(b) luminance

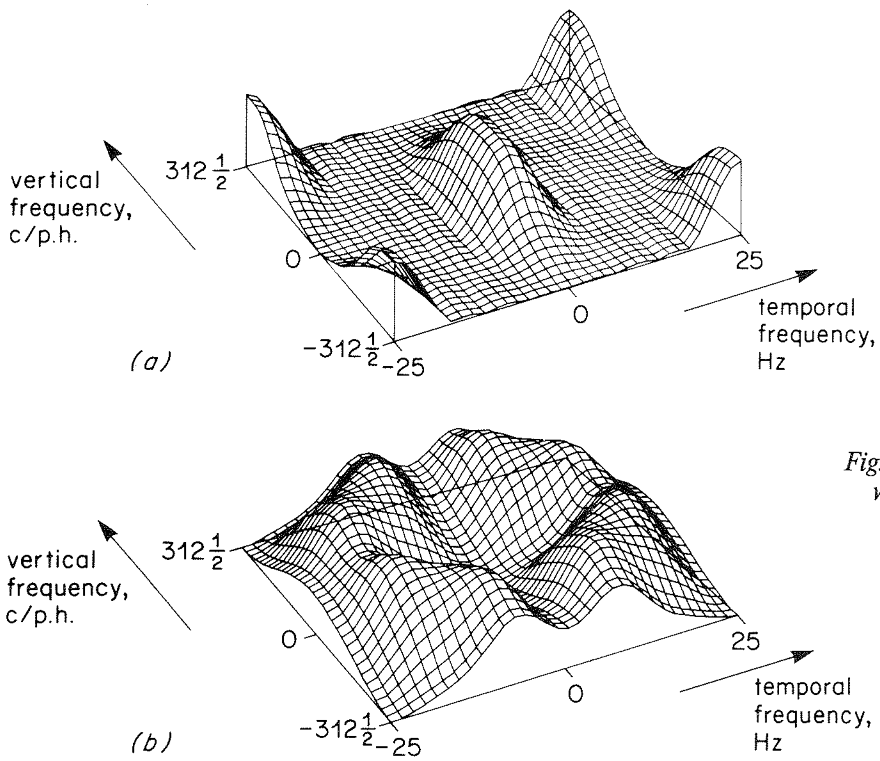


Fig. 21 - Continuous frequency characteristics which pass through the set points of Fig. 20:
(a) chrominance
(b) luminance

Table 1: Coefficient values for the 8-field decoder calculated from the fixed values shown in Fig. 20.

Contribution	Chrominance coefficient	Luminance coefficient
0	0.1562	0.6197
±1	0.0125	−0.0755
±2	−0.0031	−0.0156
±311	−0.0046	0.0
±312	0.0848	−0.0938
±313	0.0848	−0.0938
±314	−0.0046	0.0
±623	−0.0031	0.0065
±624	0.0062	0.0313
±625	0.1187	−0.1380
±626	0.0062	0.0313
±627	−0.0031	0.0065
±936	−0.0036	0.0
±937	0.0484	0.0313
±938	0.0484	0.0313
±939	−0.0036	0.0
±1248	−0.0016	0.0013
±1249	0.0	0.0065
±1250	0.0406	−0.0469
±1251	0.0	0.0065
±1252	−0.0016	0.0013

5. PERFORMANCE APPRAISAL

5.1 Decoder comparisons

With the very large number of different PAL decoding methods that have been developed, it is helpful to review some of their individual strengths and weaknesses and therefore to put into perspective the progress that has been made towards improved performance. Table 2 compares the performance of five different comb filter decoding methods against that of a conventional delay-line PAL decoder. Each of the decoders chosen is representative of a different level of complexity. The decoders are arranged in the order of increasing temporal aperture.

The performance of each decoder is compared against that of the conventional decoder using a seven-point scale. The appraisal covers eight categories of impairment consisting of luminance and chrominance resolution, cross-effects and self-effects, and the response to differential phase distortion and to movement. The assessment for movement is a composite judgement based on the response to moving saturated chrominance, that is, chrominance resolution and cross-luminance, but also takes account of cross-colour, self-effects and luminance resolution for moving objects. Because the conventional decoder performs better in some respects than in others, the comparisons are not necessarily consistent from one category to another. So, although the same grade is shown, the impairment produced by luminance aliasing in a 2-line Weston decoder is not directly comparable to that resulting from differential phase distortion.

Table 2: Comparison chart for PAL decoders

	2-line Weston	2-field	4-field	2-picture Weston	8-field
h.f. luminance resolution	+	★	★	★ ★	★ ★
vertical chrominance resolution		★	★	★ ★	★
cross-colour		+	★	★	★ ★
cross-luminance	+	★	★	★	★
luminance aliasing	◪			□	
$U-V$ crosstalk	■			◪	
differential phase	◪	■		◪	
movement				■	□

KEY: (comparisons with a conventional PAL decoder)

★ ★	–	much better
★	–	better
+	–	slightly better
	–	similar
□	–	slightly worse
◪	–	worse
■	–	much worse

Decoder details:

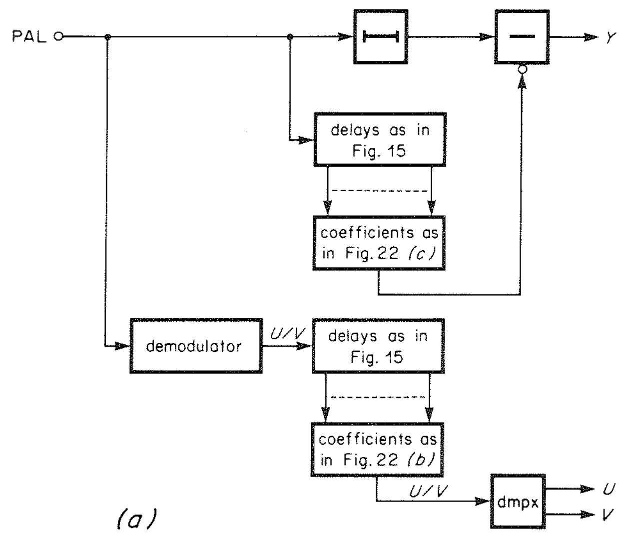
2-line Weston	:	Fig. 6(c)
2-field	:	Fig. 6(d) with 312-line delays
4-field	:	Fig. 12
2-picture Weston	:	Fig. 6(c) with 625-line delays
8-field	:	Fig. 22

The following brief description brings out the main features of Table 2. The conventional decoder is a compromise, avoiding the worst impairments, but the performance for resolution and cross-effects is generally rather poor. In comparison, the 2-line Weston decoder improves the luminance resolution, in particular, retaining the resolution bars on 'Test Card F' at full amplitude and with no cross-colour. However, this advantage is gained at the expense of a number of extra impairments. The most objectionable of these in the decoded picture is the introduction of $U-V$ crosstalk at horizontal chrominance transitions, but the most serious in the context of studio decoding is the failure to suppress plain area subcarrier in signals affected by differential phase distortion; this causes hue errors in the final decoder. Although cross-colour is removed from resolution bars, sloping luminance produces more cross-colour than normal. Also, cross-luminance impairments now affect horizontal rather than vertical colour transitions, albeit to a lesser extent.

The next development, the 2-picture Weston decoder, made spectacular improvements to still pictures, but introduced serious impairments to movement and retained the differential phase problems of the line-based method. Also, the $U-V$ crosstalk and luminance aliasing impairments were transferred from vertical detail to moving areas. In comparison, the 2-field method (which had been devised much earlier, but was first implemented as a by-product of the 2-picture Weston) gives much more acceptable performance, apart from its failure to suppress Hanover bars. The 4-field decoder is a development of this, devised to remove Hanover bars by a slight reduction of vertical and temporal chrominance resolution. This represents a reasonably satisfactory decoder in all respects, as it approaches the strengths of the 2-picture Weston method, while avoiding its weaknesses.

The resolution and cross-effects performance can be improved still further by using the extra vertical and temporal contributions of the 8-field decoder. These make it possible to use sharper temporal characteristics to retain more luminance resolution without increasing cross-luminance and to further reduce cross-colour. By choosing curves that fall to zero without a large negative response, the poor movement performance of the Weston decoder can be

avoided. The more controlled temporal characteristics of the 8-field decoder therefore only slightly degrade movement performance.



5.2 Subjective tests

The decoders shown in Table 2 have been compared in a series of subjective tests*. These tests sought to ascertain in general terms whether the increases in complexity that result from using comb filters with more contributions led to worthwhile improvements in performance. However, a more specific question was the extent to which movement performance could be sacrificed as a means of obtaining better performance in other respects.

The wide range of different impairments produced by the decoders in Table 2 makes the choice of test material particularly difficult. A set of twelve test sequences was selected to explore the different types of impairment that may arise. Brief descriptions of the test sequences and the decoder impairments to which they are sensitive are given in the Appendix. Because of the special interest in movement portrayal, the tests

* The tests were organised and conducted by A.B. Gentles.

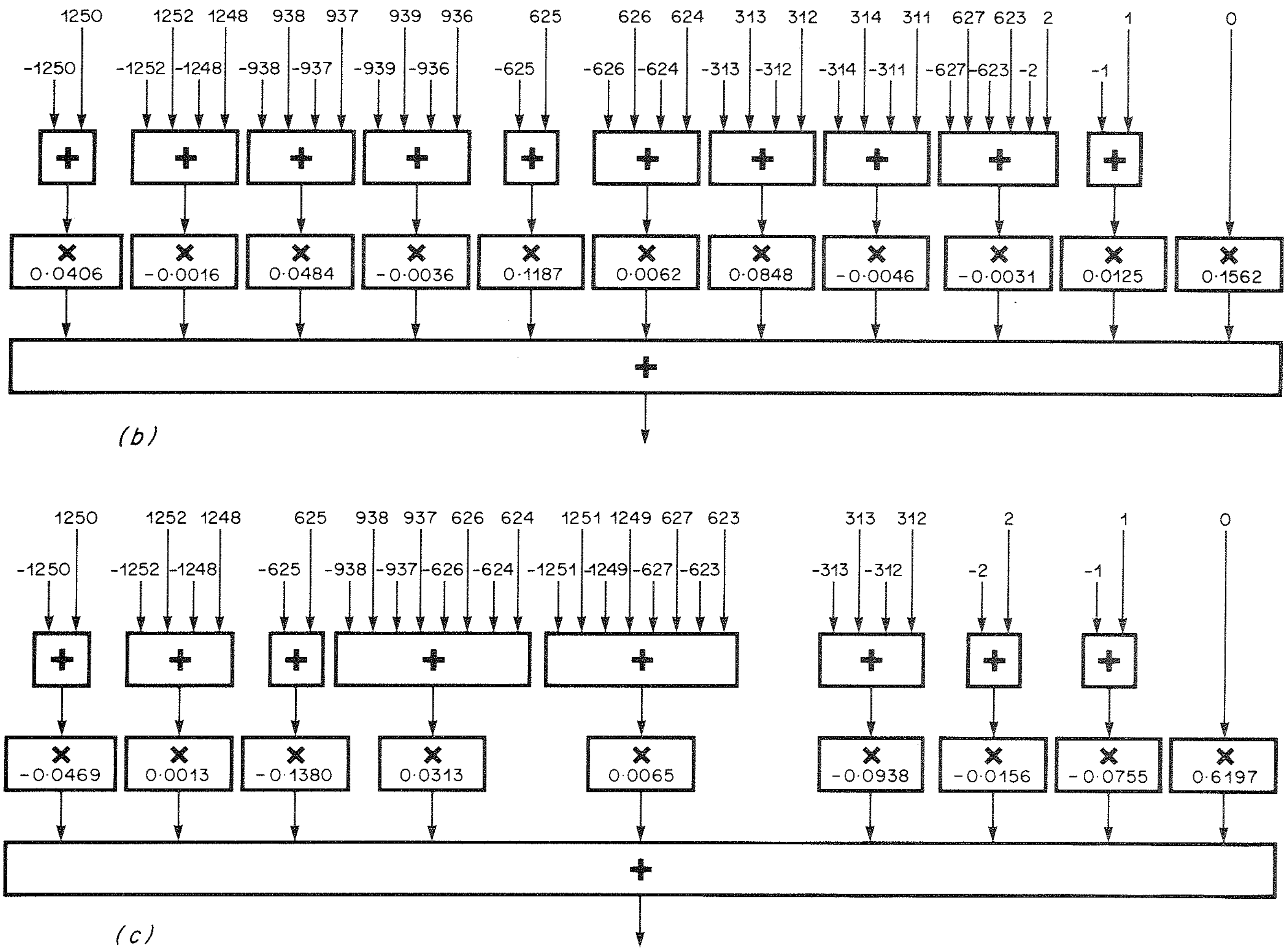


Fig. 22 - Circuitry used to combine the contributions of Fig. 16 with the coefficient weights shown in Table 1 to produce a filter with the characteristics of Fig. 21:

(a) basic circuit (b) chrominance coefficients detail (c) luminance coefficients detail

have been designed to emphasise moderately rapid, sustained motion and so do not reflect a typical sample of programme material. Nevertheless, material similar to the test sequences could arise in normal programmes.

The tests were conducted according to recommended practices[12] and used two groups of fifteen observers, one classified as experienced (having worked on picture quality in the last ten years) and the other non-experienced. The results produced by the two groups were found to be not significantly different. The tests were graded using the CCIR 5-point quality scale and the results produced for the six decoders are shown in Fig. 23. As in Table 2, the decoders are arranged in order of increasing temporal aperture.

The results for the three still picture tests are shown in Fig. 23(a) to (c). The 'Young Couple' slide predominantly tests for luminance resolution and cross-colour. Thus, as expected from Table 2, Fig. 23(a) shows that the 2-line Weston method is a slight improvement over the conventional decoder, with the 2- and 4-field decoders noticeably better, while the 2-picture Weston and the 8-field decoders provide a further substantial improvement. The main feature of the 'Orbit' computer graphics picture, on the other hand, is its abrupt transitions between saturated colours. The results in Fig. 23(b) are broadly similar to those in Fig. 23(a) except that the 2-line Weston decoder receives a significantly poorer grade. This is the result of $U-V$ crosstalk being produced at horizontal transitions between colours. The main impairment for the 2- and 4-field decoders in this case is the presence of cross-luminance at the horizontal transitions. The results for the third still picture test ('Teletext Graphics') would also have been similar except for the effects of differential phase distortion. Accordingly, in Fig. 23(c), the 2-field decoder is graded lowest, due to the presence of Hanover bars. Differential phase distortion also affects both the Weston decoders, resulting in the subcarrier not being fully suppressed in plain areas. This effect is similar in the two cases, but the 2-picture decoder receives a higher grade because of its superior performance in other respects.

Overall, therefore, there is a general improvement in performance for still pictures as the temporal aperture is increased. However, the 2-field and the two Weston decoders are adversely affected by differential phase distortion. This leaves the 4-field and 8-field decoders which give a substantial improvement over the conventional decoder, with a slight performance advantage for the 8-field method.

The remaining nine test sequences examine the movement performance of the decoders. Fig. 23(d) and (e) show the results for sustained movement of luminance as represented by the 'Pendulum' and 'Captions' sequences. In the Pendulum sequence, camera lag forms the predominant feature so that the grades received by all the decoders in Fig. 23(d) are virtually the same. The Captions sequence shows a gradually increasing advantage for the wider aperture decoders. This is due to the slightly better suppression of moving cross-colour obtained from these decoders. The 8-field decoder shows the greatest advantage in this respect.

The results for sustained movement of coloured objects, obtained from the 'Train Set' and 'Disk' test sequences, are shown in Fig. 23(f) to (i). The four tests produce a similar pattern of grades in which the conventional, 2-line Weston and the 2- and 4-field decoders all achieve broadly comparable results. The 2-picture Weston decoder is significantly poorer and the 8-field decoder falls between the two. The predominant impairment for these two decoders is the blurring or multiple imaging of moving coloured objects. The results (f) to (i) are presented in order of increasing speed of movement and show a proportionately greater spread of results for the faster movements. The results for the 'Fast Disk' even show a slight reduction in quality with the 4-field decoder, indicating that the width of its temporal aperture can become significant at the fastest rates of movement.

Whereas the previous moving sequences are somewhat synthetic, having been contrived to produce a sustained impairment to simplify assessment, the final group of results, shown in Fig. 23(j) to (l), contain a rather greater variety of movement and so may be more representative of real television programmes. The results shown in Fig. 23(j) for the 'Interview' sequence, which has an emphasis on moving high-frequency luminance, are broadly similar to those for still pictures in Fig. 23(a) to (c), with a general advantage to the larger aperture filters. In this case, however, the 2-picture Weston decoder is noticeably worse than the field-based methods, probably because of its wide range of movement impairments. The 'Show-jumping' sequence contains a variety of different types of movement and includes moving areas of both luminance detail and saturated colour. Fig. 23(k) shows that the conventional decoder is best for this sequence, with the 2-, 8- and 4-field decoders following in order closely behind. Both Weston decoders are noticeably poorer, probably because of increased cross-effects, $U-V$ crosstalk and moving chrominance impairments. The main feature of the 'Snooker' sequence is the movement of the coloured balls against the static green background. As in the results (f) to (i), the conventional, 2-line Weston and 2- and 4-field decoders produce broadly similar grades, but the 8-field decoder in this case produces slightly more impairment than the 2-picture Weston method.

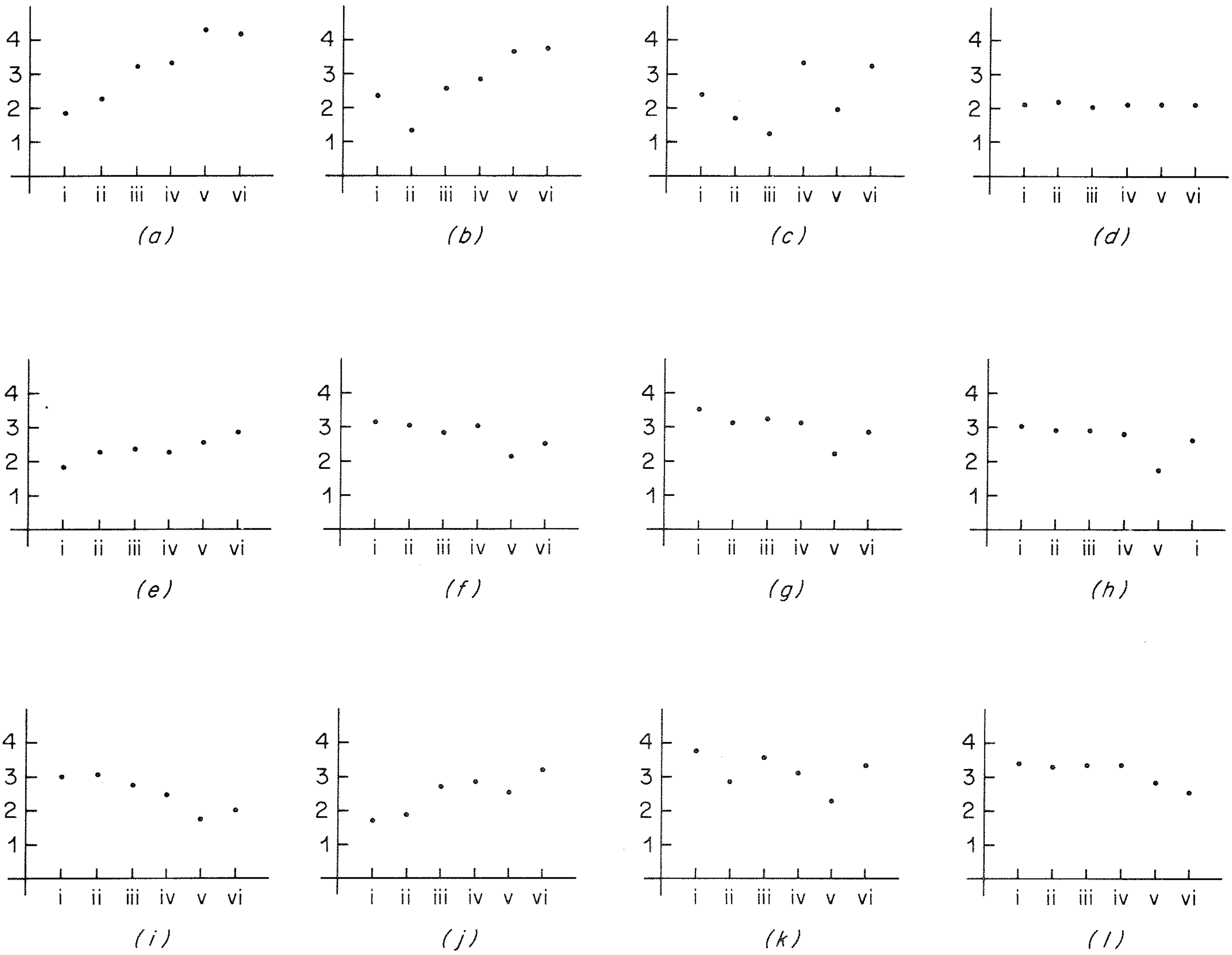


Fig. 23 - Subjective test results for the six decoders:

(i) conventional
(ii) 2-line Weston
(iii) 2-field
(iv) 4-field
(v) 2-picture Weston
(vi) 8-field

These are compared for each of the twelve test sequences listed below.

(a)	'Young Couple'	still pictures
(b)	'Orbit'	
(c)	'Teletext Graphics'	
(d)	'Pendulum'	moving pictures
(e)	'Captions'	
(f)	'Train Set 1'	
(g)	'Train Set 2'	
(h)	'Rotating Disk'	
(i)	'Fast Disk'	
(j)	'Interview'	
(k)	'Show-jumping'	
(l)	'Snooker'	

The vertical scale is the CCIR 5-point quality scale:

1 Bad
2 Poor
3 Fair
4 Good
5 Excellent

5.3 Discussion of results

Taking an overall view of the results, some of the decoders are ruled out by particularly poor performance in one or more of the tests. For example, the 2-field decoder receives a very low grade for test (c) because it fails to suppress Hanover bars, although frequently figuring amongst the best grades for the other tests. Also, the 2-picture Weston method is consistently poor for movement and, when differential phase distortion is present, leaves the subcarrier unsuppressed in plain areas. The 2-line version, on the other hand, is generally amongst the best for sustained movement, but is rather poor in other cases, especially for still pictures.

Only the 4-field decoder provides performance that is consistently either 'fair' or at least comparable with the best grades for that test. The 8-field decoder, however, can attain appreciably higher grades than the 4-field method, providing an improvement of up to one grade in some of the still picture tests. This is offset by sometimes more than half a grade poorer performance when the picture material contains sustained movement of saturated colours, such as in the Train Set and Disk tests and in the Snooker sequence.

Whereas it might be argued that the tests place a disproportionate emphasis on moving saturated colours, which the 8-field decoder finds difficult, the question remains as to whether a grade midway between 'fair' and 'poor' is sufficient for material such as Snooker. Certainly a higher grade would be preferred and could be achieved with an 8-field decoder by using a less abrupt temporal chrominance characteristic, more similar to that of the 4-field method. However, because the decoder design is essentially a trade-off between different impairments, a consequence of this would be that some of the advantage over the 4-field method on other picture material would be lost. If practical considerations are included, the much lower complexity of the 4-field arrangement, both in storage costs and because of its particularly simple coefficient values, is likely to outweigh the limited performance advantage that an 8-field decoder might bring.

6. CONCLUSIONS

The structure of PAL television signals in the vertical–temporal frequency domain has been used to provide a review of the main developments in non-adaptive comb filters for chrominance–luminance separation. Four basic techniques using line delays have been described. These arise from different approaches to accommodating the complicated sub-carrier phase and *V*-switch relationships between lines of the PAL signal. The extension of the line-based techniques to use field and picture delays has then been considered and a number of promising techniques identified. An increased level of complexity has been examined by combining line and field delays to make multi-tap filters with improved performance.

A further advance in performance has been sought by developing a technique to synthesise a vertical–temporal frequency characteristic with the desired response, within the constraint of a limited filter aperture. The aperture dimensions control the number of positions at which the frequency response can be set independently. Using the technique, a new decoder was designed with an aperture of eight fields and up to five lines per field with a view to improving performance by using a narrower temporal response.

The 8-field decoder was compared in a series of subjective tests against five other decoders, representative of several different levels of complexity ranging upwards from that of a conventional delay-line decoder. The tests showed that although useful improvements in performance could be obtained on many pictures using the 8-field decoder, there was a noticeable increase in impairment for rapidly moving areas of saturated colour. A 4-field multi-tap decoder, however, did achieve a consistently high standard of performance on all pictures compared with a conventional decoder, although not quite matching the performance of the 8-field method in some respects.

The movement impairments of the 8-field decoder could be reduced by developing a new set of coefficients which produce a more gradual roll-off in the temporal frequency response. However, this is likely to reduce the advantage over the 4-field decoder for other picture material. In view of this, and the relative simplicity of the 4-field method, it appears that the extra complexity of the 8-field decoder is difficult to justify for the limited improvement in performance that might be obtained.

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APPENDIX

Description of Test Sequences

(a) 'Young Couple'	An EBU test slide containing a striped shirt and check material. The slide primarily tests for high-frequency luminance resolution and cross-colour.
(b) 'Orbit'	A computer graphics picture containing a variety of fine curved lines which make abrupt transitions between saturated colours. Primarily tests for chrominance resolution and $U-V$ crosstalk, but also provokes some fine cross-colour and cross-luminance.
(c) 'Teletext Graphics'	The relatively coarse blocks of the teletext system produce large areas of saturated colour with abrupt horizontal and vertical transitions between them. The sequence was recorded off-air and had been seriously affected by differential phase distortion.
(d) 'Pendulum'	A black-and-white striped pendulum swings from side-to-side through the field of view against a blue background. Camera lag causes noticeable trails from the white parts of the pendulum. The test proved insensitive to decoder impairments.
(e) 'Captions'	The sequence consists of white letters scrolling vertically against a black background in the manner of programme credits. The letters provoke cross-colour.
(f) 'Train Set 1'	A view of a model train moving forwards and backwards across the field of view. Although the scene contains general detail, the most testing feature of the sequence is the sustained linear movement of the highly coloured trucks.
(g) 'Train Set 2'	A close-up the train in (f) viewed from a lower angle, but with the speed of the train reduced to give approximately the same rate of movement on the screen. Also sensitive to moving colour impairments.
(h) 'Rotating Disk'	The screen is filled by the top half of a rotating disk to which are attached a number of black-and-white and coloured pictures and printed characters. Mainly for colour movement impairments, but also produces some cross-colour.
(i) 'Fast Disk'	The same disk as in (h), but rotating more rapidly.
(j) 'Interview'	This sequence shows an animated conversation in which one of the participants is wearing finely striped clothes. This moving luminance detail results in cross-colour which changes frequency as the camera gradually zooms in for a close-up.
(k) 'Show-jumping'	The white woodwork of the fences and the red jacket of the rider provide a lot of moving detail as the camera follows the rider round a jumping course. Sensitive to cross-colour and moving chrominance effects.
(l) 'Snooker'	The general scene is static, showing the coloured balls moving quite rapidly against the green surface of the table. The linear movement of the balls provides a particularly sensitive test for moving chrominance effects.